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THESIS

A STUDY OF A RAPID CYCLOGENESIS EVENT DURING GALE

by

Jeffrey L. Carson

June 1988

Thesis Advisor Carlyle H. Wash

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An explosive cyclone that developed during intensive observation period (IOP) 9 of the Genesis of Atlantic Lows Experiment (GALE) is studied. Detailed surface analysis is conducted based on operationally available data, late reporting ship observations and special observations acquired by GALE scientists to determine the surface storm track and deepening rate. GALE dropsonde and rawinsonde data are used to supplement the normal upper-level data base, and are analyzed by the Navy Operational Regional Analysis and Prediction System (NORAPS) using optimal interpolation objective analysis. These analyses are discussed with special emphasis given to possible factors contributing to the explosive cyclogenesis. Factors that influenced the cyclone's rapid development include upper-level postive vorticity advection, low-level warm temperature advection and low-level instability. Vertical soundings and cross-sections utilizing the dropsonde and rawinsonde data are used to study the environment in which the rapidly deepening cyclone initially developed.

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A Study of a Rapid Cyclogenesis Event During Gale

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An explosive cyclone that developed during intensive observation period (IOP) 9 of the Genesis of Atlantic Lows Experiment (GALE) is studied. Detailed surface analysis is conducted based on operationally available data, late reporting ship observations and special observations acquired by GALE scientists to determine the surface storm track and deepening rate. GALE dropsonde and rawinsonde data are used to supplement the normal upper-level data base, and are analyzed by the Navy Operational Regional Analysis and Prediction System (NORAPS) using optimal interpolation objective analysis. These analyses are discussed with special emphasis given to possible factors contributing to the explosive cyclogenesis. Factors that influenced the cyclone's rapid development include upper-level postive vorticity advection, low-level warm temperature advection and low-level instability. Vertical soundings and cross-sections utilizing the dropsonde and rawinsonde data are used to study the environment in which the rapidly deepening cyclone initially developed.

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I. INTRODUCTION

Weather events of an extreme nature, like tornadoes, hurricanes and droughts, often make headlines in the media, peaking the interest of the general public and the meteorological community. A similar phenomenon, explosive cyclogenesis, has captivated the research interest of meteorologists this decade. Because the physical processes leading to rapid development of extratropical cyclones are not fully understood, contributing to the failure of numerical models to accurately predict rapid deepening, explosive cyclogenesis has been the topic of numerous studies and papers over the past ten years.

Explosive cyclogenesis was defined by Sanders and Gyakum (1980) as a developing cyclone with central pressure falls of at least 1 mb h^{-1} for 24 h at 60°N. Their study suggested that explosive cyclogenesis is mainly a maritime or coastal event, with a maximum frequency over the western North Atlantic and Pacific Oceans. A correlation between the sea-surface temperature gradients of these regions and rapid cyclogenesis events was found, with most explosive cyclones developing just to the north of the Gulf Stream and Kuroshio currents.

The Sanders and Gyakum study focused interest on the explosive cyclogenesis problem and spurred further research of this potentially dangerous event. Utilizing weather ship rawinsonde data, Rogers and Bosart (1986) created three-dimensional composites of the development stages of Atlantic explosive cyclones and a composite sounding of the environment near Pacifc explosive cyclones. 328 storms were used to create these composites. They found that rapidly developing cyclones often have their beginnings in weak, shallow systems that then mature into intense cyclones. Characteristics of these more mature storms include strong baroclinicity, strong upward motion and low-level conditional instability.

Numerous case studies have been completed investigating the development of explosive cyclones. Two of the better known cases deal with the Queen Elizabeth (QE) II Storm of 1978 and the Presidents' Day Snowstorm of 1979. During the QE II Storm, which developed on 10-11 September 1978, the central pressure fell almost 60 mb in 24 h. The luxury liner QE II felt the brunt of the hurricane force winds and heavy seas associated with this western North Atlantic storm. Using surface wind data from Seasat-A in addition to ship, buoy and land reports, Gyakum (1983a,b) described the

synoptic, dynamic and thermodynamic processes that contributed to the explosive development. Gyakum showed that a diagnostic, quasi-geostrophic model could not account for the extreme deepening that occurred. He suggested that the diabatic processes associated with the convective activity were instrumental in the explosive deepening of the storm. This concept is similar to the CISK mechanism evident in tropical cyclones.

Anthes et al. (1983) conducted numerical simulations of the development of the QE II Storm while varying the physical processes and initial data that were included in the model. Inclusion of latent heat effects, sensible heat fluxes, cumulus parameterization and boundary layer parameterization provided for a more accurate depiction of the observed development. However, no one process could be attributed as being the cause of the explosive deepening. Two data sets were used to initialize the model: a set of operationally available data and the supplemented data used by Gyakum previously mentioned. The model performed significantly better when initialized with the supplemented data set. In later study, Uccellini (1986) showed that upper-level baroclinic processes played a more significant role in the explosive development of the QE II Storm than first thought. His analyses included evidence of upper-level positive vorticity advection and divergence that aided the surface cyclogenesis and contradicted Gyakum's claims that upper-level features had only a a small influence on the surface development.

The Presidents' Day Snowstorm of 18-19 February 1979 brought record snowfall amounts to Washington, D.C., and portions of Virginia, Maryland and Delaware. Bosart (1981) described the development of this coastal system which began as a weak low off the North Carolina coast. He showed that the low began to intensify as a short wave approached the east coast from the Ohio Valley. This upper-level support combined with the diabatic heating associated with the observed convection were given as major factors for the storm's explosive nature. As in the QE II Storm, the latent heat associated with the convection and the sensible heat fluxes from the ocean surface added to the instability of the storm's environment.

Uccellini, et al. (1987) ran several numerical simulations of the Presidents' Day Storm. The results from these simulations show that the diabatic processes, associated with the convection and surface heat and moisture fluxes, were interrelated with the dynamic processes associated with the observed temperature advections and jet steak patterns. Because each process tended to enhance the other, it was difficult to rank the importance of the different low- and upper-level forcing mechanisms. In essence, processes throughout the entire atmosphere need to be considered when explaining explosive

cyclogenesis. Uccellini, et al. (1986) also discussed the possible contibutions to the explosive cyclogenesis by warm, dry stratospheric air introduced by tropopause folding.

A. THE GENESIS OF ATLANTIC LOWS EXPERIMENT

Rogers and Bosart (1986) pointed out that the primary problem with studying rapid cyclogenesis is lack of data. As discussed, explosively developing cyclones tend to form in the western oceans where there are no regular rawinsonde or surface reporting stations. As a result, it has been difficult to pinpoint the physical and dynamical atmospheric processes that produce rapid cyclogenesis.

In an effort to study rapid cyclogenesis more thoroughly, the Genesis of Atlantic Lows Experiment (GALE) was conducted from 15 January through 15 March 1986. GALE was an inter-agency project and included the participation of the National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA), Department of Defense, and numerous governmental agencies and universities. One of the primary goals of GALE, as outlined in the GALE Field Program Summary (1986), was to further the understanding and knowledge of east coast winter storms, including those experiencing rapid cyclogenesis.

The center of GALE activity was eastern North and South Carolina, where an extensive atmospheric sounding network was established. However, the area of interest was extended to an area covering most of the eastern United States and portions of the western North Atlantic Ocean when the weather conditions warranted the expanded coverage. Satellites, radar, research aircraft, Air Force weather reconnaissance aircraft, research ships and different boundary layer platforms acquired data for research purposes. GALE observations were focused on Intense Observation Periods (IOPs) when additional observations were taken to enlarge the meteorological data base.

The objective of this thesis is to study the events in IOP 9, particularly from 0000 UTC 25 February until 0000 UTC 26 February 1986. During this period, a cyclone off the coast of North and South Carolina deepened rapidly as it moved to the northeast. With the addition of GALE data and late reporting ship observations, the synoptic development of this cyclone is documented. The structure of the environment that produced rapid cyclogenesis is also explored using data acquired from GALE dropsonde missions.

II. SURFACE ANALYSIS DISCUSSION

The discussion of the IOP 9 cyclone will start with a complete surface reanalysis for the western North Atlantic Ocean. The goal of this section is to document the track and intensity of the cyclone using newly available GALE data to supplement operational observations. Early discussions of this case are found in the GALE Field Program Summary (1986) and Pertle (1987).

The explosive cyclogenesis event that occurred during IOP 9 was a result of an upper-level short wave trough moving off the east coast of the United States in the wake of an earlier surface cold front. Using Navy Operational Regional Analysis and Prediction System (NORAPS) analyses, Pertle (1987) detailed the synoptic situation for the twelve hours prior to the beginning of IOP 9. A review of this time period is appropriate before discussing the developments of IOP 9.

At 1200 UTC 24 February 1986 (Fig. 1), the eastern half of the United States is under the influence of a long wave trough. A vorticity maximum associated with a short wave trough moving through the long wave pattern is evident over the Ohio Valley. The western part of the country is dominated by a long wave ridge. Over the western North Atlantic Ocean there is also weak evidence of short wave activity.

The sea-level pressure analysis (Fig. 2) shows a closed low pressure center of 1009 mb over eastern Kentucky. This low pressure center is associated with the 500 mb short wave over the Ohio Valley. The National Weather Service (NWS) analyzed a cold front extending from this low center through western Tennessee, southern Arkansas and into northeastern Texas. A weak warm front extends from the low into southern South Carolina. Offshore, a pressure trough extends from a low pressure center near 47°N, 54°W, south of Newfoundland, to near 31°N, 70°W. The NWS analyzed a weak cold front through this trough, with the front becoming stationary through the Florida Straits. The new surface analyses for 0000 UTC 25-26 February which follow are based on operationally available data, late reporting ship data, GALE ship and buoy data, GALE dropsonde data and GOES satellite data.

A. SURFACE DISCUSSION FOR 0000 UTC 25 FEBRUARY 1986

By 0000 UTC 25 February the low pressure center originally over eastern Kentucky has moved east of the northern South Carolina coast to near 33°N, 75°W. As indicated in Fig. 3, the system has deepened slightly during the previous twelve hours, with the

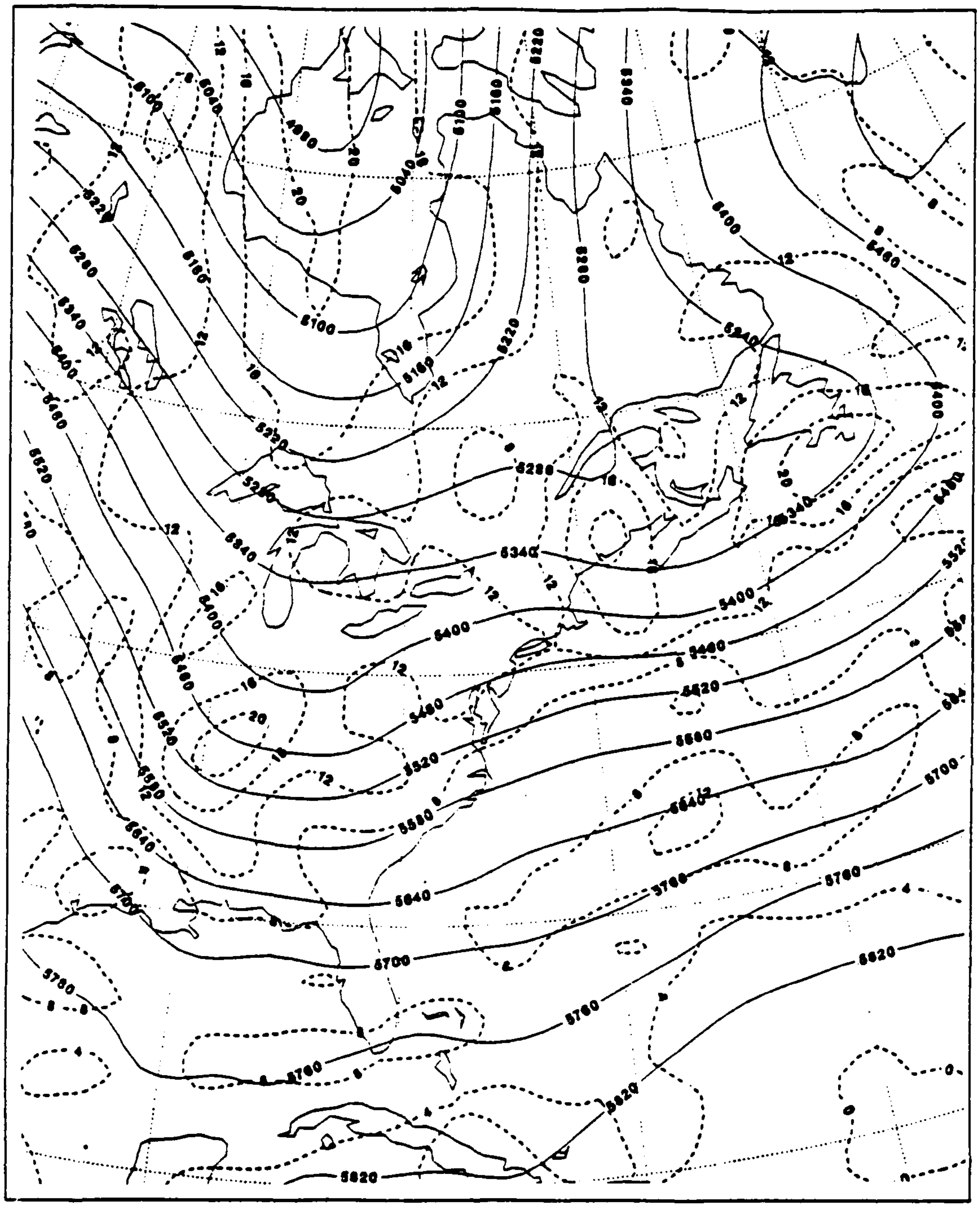

Fig. 1. NORAPS operational 500 mb analysis valid 1200 UTC 24 February 1986: Heights (m) and absolute vorticity ($10^{-5}s^{-1}$)

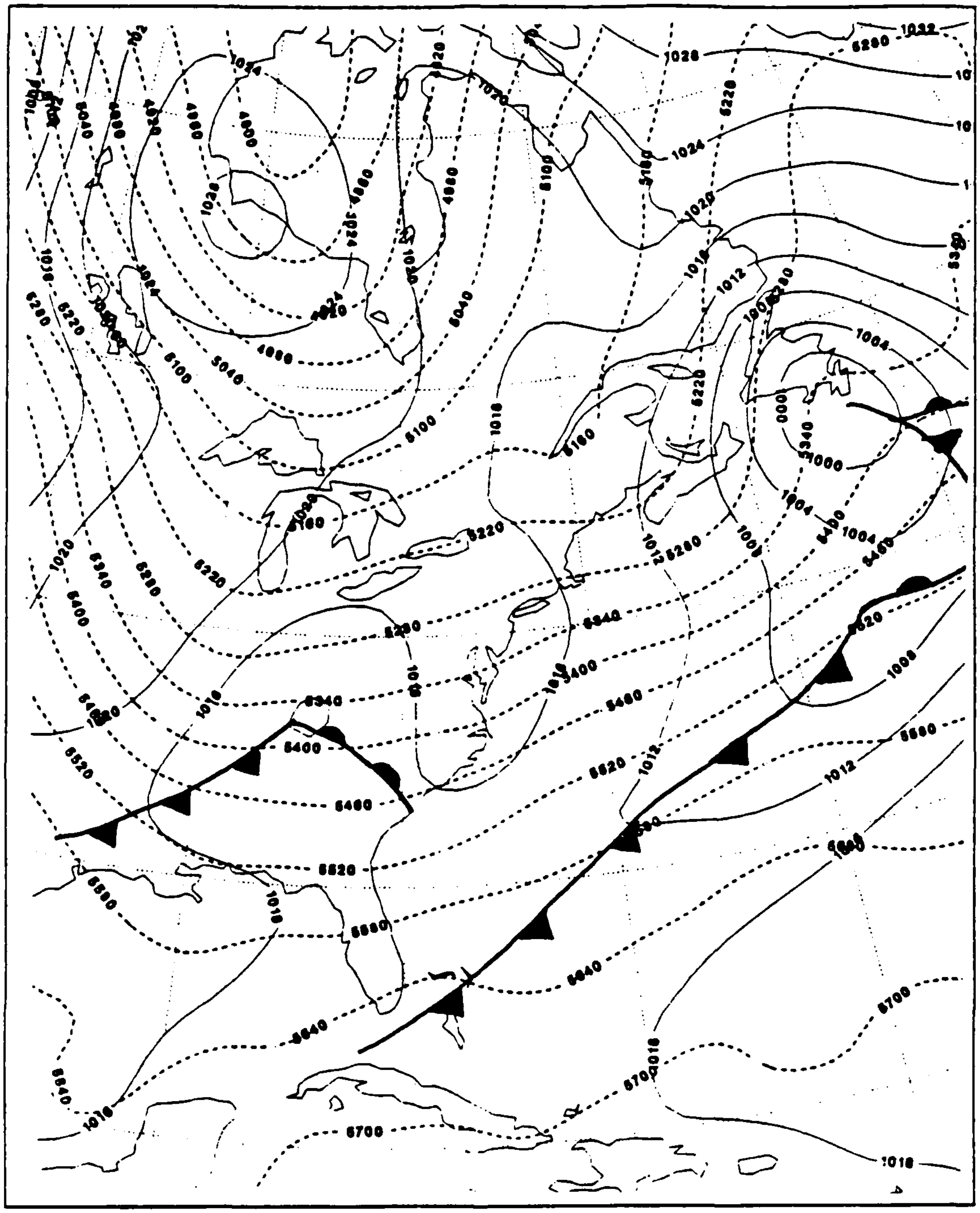

Fig. 2. NORAPS sea-level pressure analysis (mb) and NWS frontal positions valid 1200 UTC 24 February 1986

pressure dropping from 1009 mb to 1005 mb. A cold front extends back from the low through central Georgia, while a weak inverted trough stretches to the north from the low, along the coast to Virginia.

A second feature evident in Fig. 3 is a second low pressure center that developed further to the east of the first low, near 33°N, 72°W. The central pressure associated with this eastern low is 1005 mb. A weak cold front extends from this low to near 30°N, 77°W and a warm front stretches from the low toward the northeast to near 38°N, 66°W.

GALE dropsonde data played a vital role in determining the exixtence of this second low or eastern surface trough. The track of the NOAA Citation dropsonde mission between 2130 UTC 24 February and 0800 UTC 25 February flew between the two low centers, and the relatively higher sea-level pressures measured suggests that in fact there are two low pressure centers provided the pressure values are accurate. However, most of these data was acquired in the vicinity of the western low and showed that the western low was still the stronger of the two centers. Low-level wind observations from the dropsondes and surface reports from the research ship Cape Hatteras help verify this fact. The dropsonde at 33°N, 74°W, located east of the low, shows south-southwesterly winds of 15 kt at 940 mb, the lowest level at which winds were reported. Surface winds from the northwest at 8 kt were reported by the Cape Hatteras, located west of the low near 33°N, 77°W. A dropsonde south of the low, near 32°N, 75°W, observed west-southwesterly wind at 15 kt, while a dropsonde north of the low reported north-northwesterly winds also at 15 kt. Both of these reports were near the 950 mb level and helped to confirm the circulation around the low. This cyclonic circulation clearly defines the western center and suggests the eastern center or trough is weaker. Dropwinsondes continued to aid in determining the strength and position of the low centers through the first 18 hours of cyclone development.

The GOES infrared imagery (Fig. 4), valid at 0031 UTC, shows a large cloud mass over the eastern Carolinas, middle Atlantic states, New England and the adjacent western North Atlantic Ocean. Frontal clouds are evident stretching from the western low back through central Georgia. A short line of clouds associated with the front from the eastern low also can be detected. A long band of cloudiness associated with the subtropical flow and the remnants of an earlier front that moved through the region extends from the Florida Straits to near 35°N, 60°W. This cloud area was described as a surface cold front on the operational NWS analysis (not shown), but the lack of surface

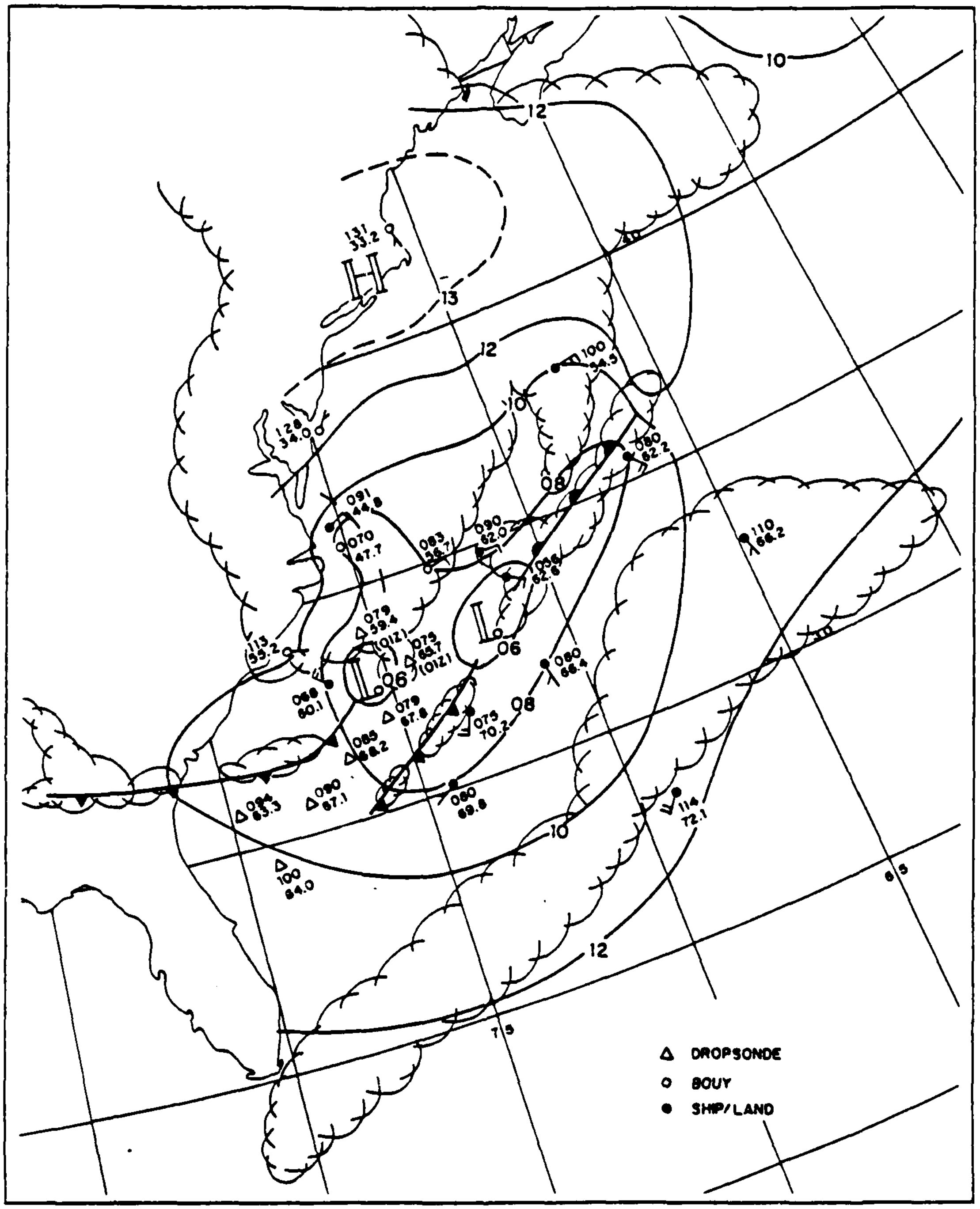

Fig. 3. **Sea-level pressure analysis, key observations and major cloud areas valid 0000 UTC 25 February 1986:** Pressure (mb), temperature (°F), wind speed (kt)

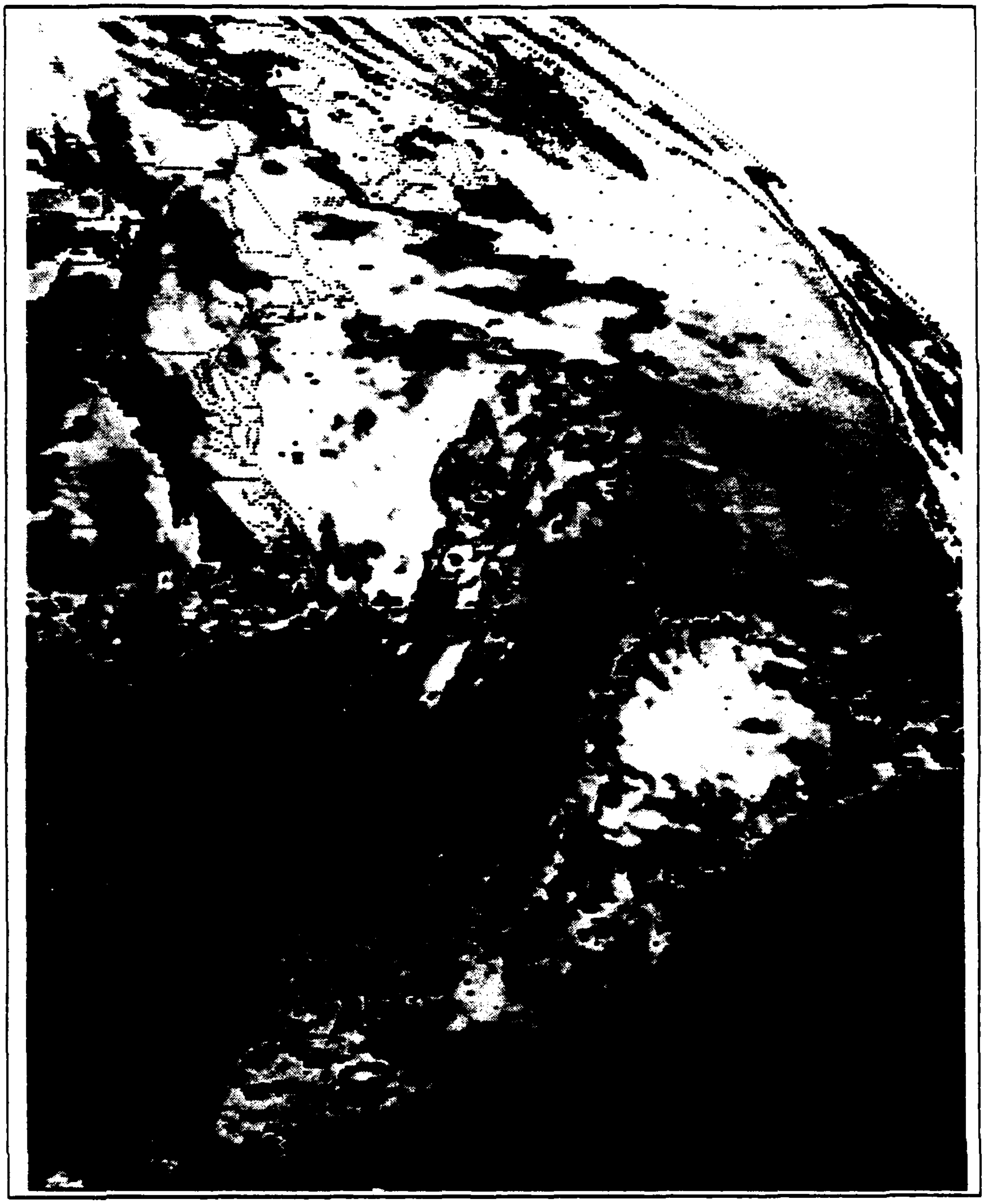

Fig. 4. EC enhancement of GOES infrared imagery valid 0031 UTC 25 February 1986

data in the vicinity of this cloud band (Fig. 3) makes it difficult to determine any frontal characteristics.

B. SURFACE DISCUSSION FOR 0600 UTC 25 FEBRUARY 1986

The surface analysis valid 0600 UTC (Fig. 5) indicates that the two lows have continued to intensify and move slowly toward the northeast. The western low has deepened 7 mb during the previous 6 hours and is now at 999 mb. This low is positioned near 33°N, 74°W. The cold front associated with this pressure center extends to the southwest through central Florida.

The eastern low, now located near 35°N, 68°W, has continued to deepen also. The exact position of the low at this time is uncertain due to the lack of data near the center. The given position is based on continuity and surface reports further from the center. The central pressure is estimated to be 997 mb at 0600 UTC, an 8 mb drop over the six-hour period. The low has begun to take on an elongated shape at this time, stretching out along the warm front that extended from the low to near 36°N, 59°W. This warm frontal trough position correlates very well with the location of the strong sea-surface temperature gradient between the Gulf Stream and the colder water to the north. Strong easterly flow is indicated ahead of the warm front, with a maximum observed surface wind of 40 kt located north of the low. A weak cold front extends from the low to near 34°N, 77°W.

The GALE dropsonde data again helped to complete an accurate surface analysis for this time period. The previously mentioned Citation dropsonde mission continued to fly between the lows until 0600 UTC. These observations indicate relatively higher pressures between the two lows. However, the low-level wind reports also indicate that the circulation around the western low is weakening. West of the low, the Cape Hatteras, still near 33°N, 77°W, observed northwesterly surface winds at 23 kts. South and southwest of the low, dropsonde 930 mb level winds near 32°N, 75°W and 31°N, 77°W were from the west at 23 and 26 kt respectively. However, dropsonde winds at 930 mb east of the low near 33°N, 74°W and northeast of the low near 34°N, 73°W and 35°N, 74°W reported northwesterly winds from 10 to 20 kt indicating that the eastern low is beginning to strengthen. This wind data suggest the possibility that the western low is simply an elongated trough west to southwest of the primary system.

GOES infrared imagery (Fig. 6) valid at 0630 UTC shows a a rather chaotic cloud pattern over the western North Atlantic Ocean. A large area of cloudiness extends from the western low back into central Georgia and South Carolina. The surface front from

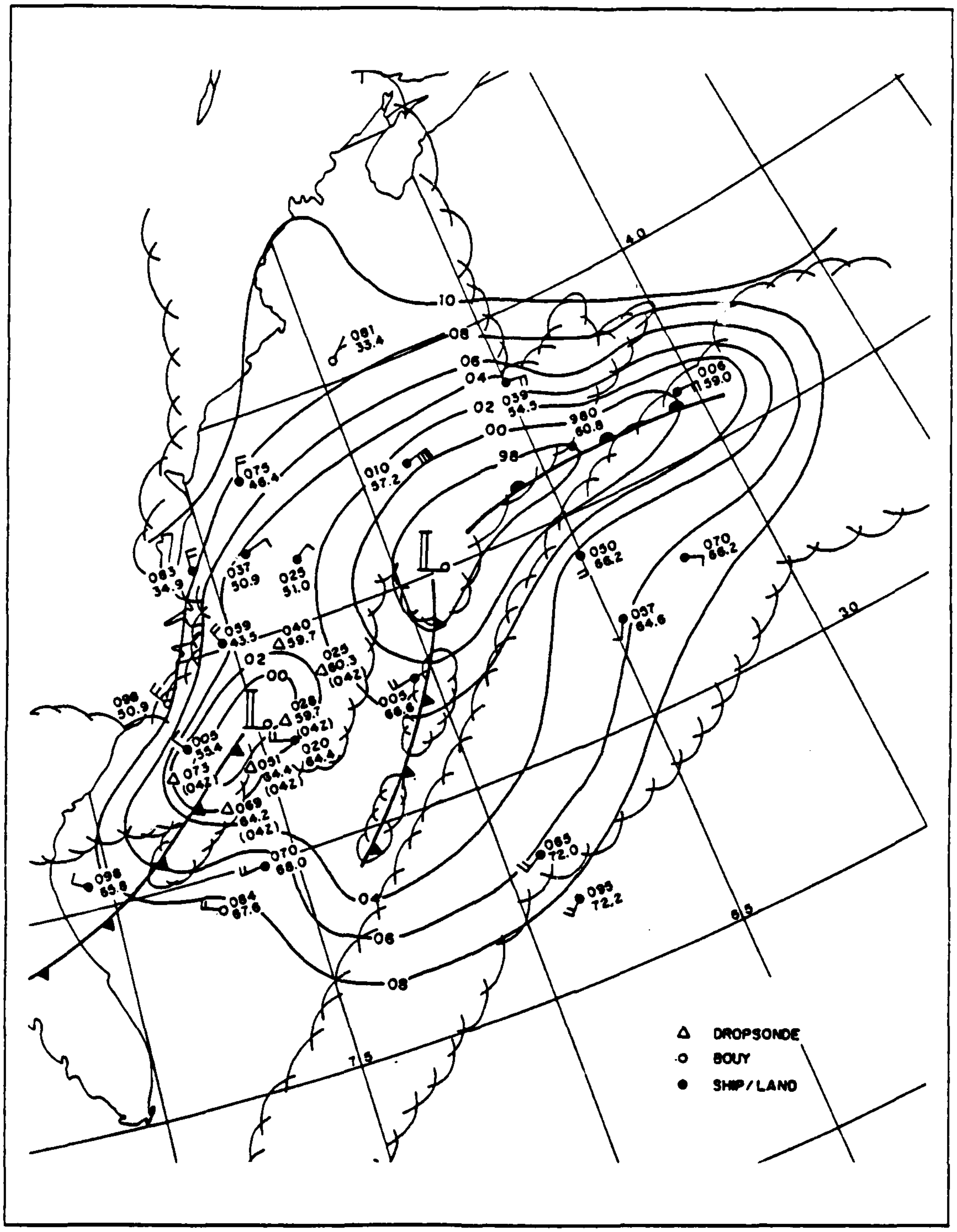

Fig. 5. Same as Fig. 3 valid 0600 UTC 25 February 1986

Fig. 6. EC enhancement of GOES infrared imagery valid 0630 UTC 25 February 1986

this low runs through northern Florida, and is evident by a short line of thick high clouds extending to near 30°N, 78°W. There is also an indication of either thin cirrus or lower clouds along the front across northern Florida.

High cloudiness associated with the front extending from the eastern low pressure center is fragmented, but appears to be more organized than the data indicated six hours earlier. There is also the appearance of what looks to be a dry slot forming near this low center at 35°N, 70°W, Enhanced cloudiness shown by the black area of the EC enhancement curve (cloud top temperatures are less than -60°C) suggests a region of vigorous vertical motion is immediately north of the cyclone.

The cloudiness associated with the subtropical flow and old front stretches from central Cuba to near 38°N, 54°W, and has thickened and widened. Again, the lack of data in this region (Fig. 5) makes it difficult to determine the frontal characteristics of this boundary. Although the position of this cloud band is within one or two degrees of the front extending from the eastern low, the cloud band appears to remain seperate from the cloudiness associated with the low pressure centers.

C. SURFACE DISCUSSION FOR 1200 UTC 25 FEBRUARY 1986

The surface analysis valid 1200 UTC (Fig. 7) indicates that the eastern low pressure center is now the dominant cyclone, while the western low center or trough weakens. The deepening rate of the western low, now located near 34°N, 72°W, has slowed dramatically. The central pressure has dropped only 2 mb during the previous six hours to 997 mb; however, the actual value of the central pressure is difficult to determine. The Citation flew a second dropsonde mission which lasted from 0820 UTC to 1730 UTC 25 February. Some of these data in the vicinity of the low indicate slightly higher pressures, while ship and other dropsonde data suggest a lower pressure. The dropsonde wind data continue to show weakening of the circulation around the western low. Northwest and north of the low, near 37°N, 74°W and 35°N, 73°W, dropsonde observations near the 940 mb level show northerly winds from 15 to 20 kt. Northwesterly winds are reported at 930 mb northeast of the low near 33°N, 72°W at 7 kt and southwest of the low near 34°N, 73°W at 21 kt. Southeast of the low, a ship report of southwesterly winds at 20 kt hint of the weakening circulation. Despite the slower deepening, the cold front extending from the low center back through southern Florida is still evident in the surface data, with a temperature gradient of 10°F across the front.

Meanwhile, the eastern low pressure center continues to deepen rapidly. At 1200 UTC the central pressure is 991 mb, a drop of 6 mb during the previous six hours. Ship

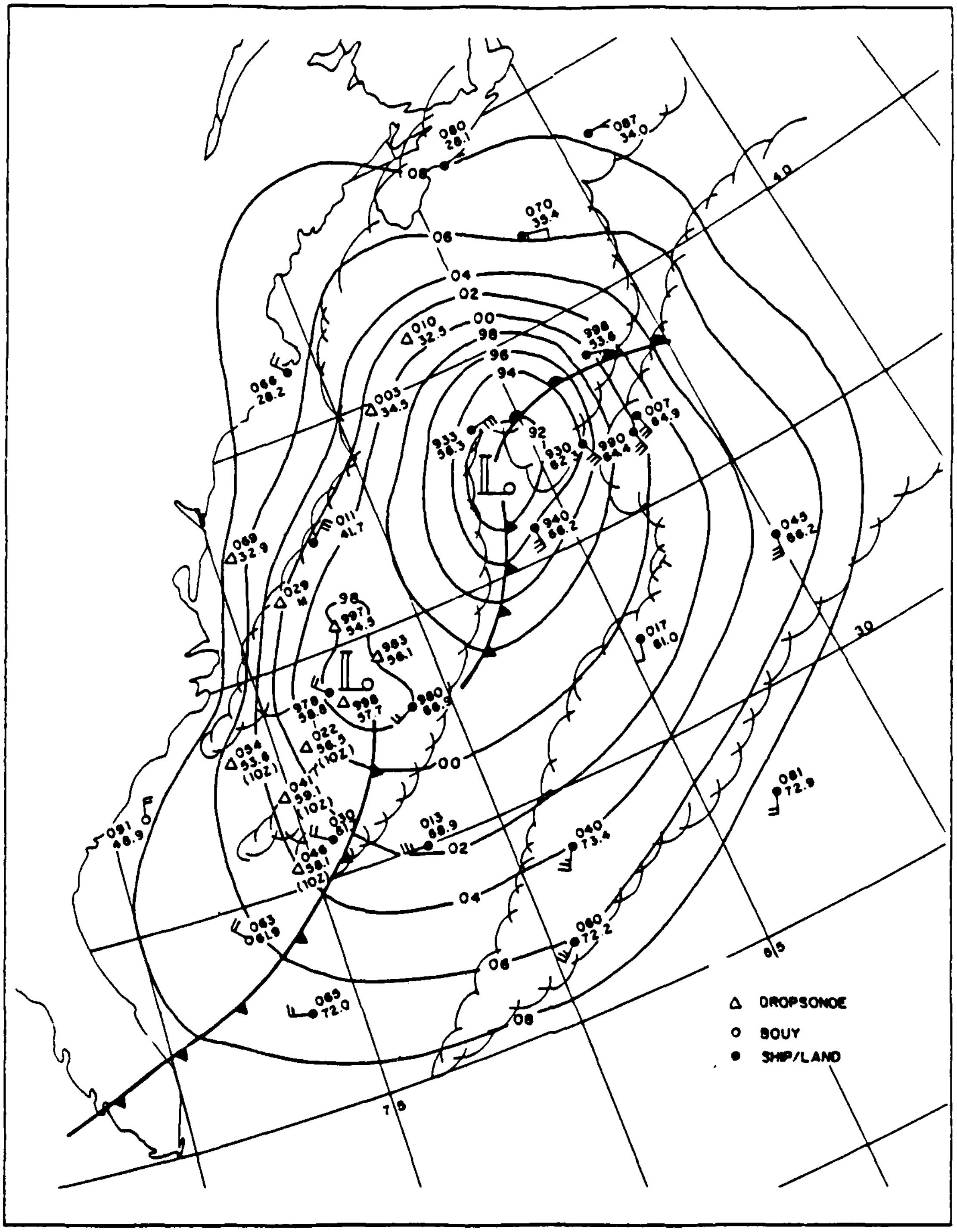

Fig. 7. Same as Fig. 3 valid 1200 UTC 25 February 1986

reports in the vicinity of the low center define this central prssure and helped to locate the low near 37°N, 66°W. Several of these ships reported wind speeds of 30 kt, supporting the tightening of the pressure gradients seen in the analysis. A weak cold front extends from the low to near 33°N, 69°W. A substantial warm front stretches to near 38°N, 60°W. Temperatures in the warm sector are quite warm with ship reports from between the warm front and 35°N ranging from 62.3 to 66.2 °F.

The GOES visual imagery from 1231 UTC (Fig. 8) shows what appears to be a comma cloud pattern associated with the western low pressure center. With closer inspection, a fairly solid deck of lower clouds is also apparent below this higher cloud feature. High cloudiness follows the front from this low to near 30°N, 75°W. Low clouds continue to mark the front across southern Florida and into the Gulf of Mexico.

The eastern low pressure center appears tc be located near the formation of a dry slot in the cloud pattern stretching from 35° N, 67°W to 38°N, 67°W. The cold front appears as a line of convection along the eastern edge of the dry slot. A region of embedded convection is present north and northeast of the cyclone and its dry slot.

The old frontal region is still well defined by a band of cloudiness stretching northward from eastern Cuba. There appears to be some bulging near the northern end of this cloud band, but no evidence of the formation of a new frontal wave is present at the surface. This cloudiness, although expanding, continues to remain separate from the cyclone cloud mass.

D. SURFACE DISCUSSION FOR 1800 UTC 25 FEBRUARY 1986

By 1800 UTC, the explosive nature of the eastern cyclone is readily apparent. The surface analysis (Fig. 9) shows that this low center pressure has become the dominant synoptic feature in the western North Atlantic Ocean. The low center is located near 39°N, 65°W with a central pressure of 983 mb. This pressure value indicates a drop of 8 mb during the previous six hours. Ship reports verify the position and intensity of the low, with the lowest pressure observation of 985 mb east of the low center. Southerly winds at this location also help to position the low. The maximum observed winds in the vicinity of the low center was 40 kt. The western low pressure center has all but dissappeared, and is reflected on the surface analysis as a trough located off the coast of North Carolina.

The remnants of the cold front from the western low has merged with the front from the dominant low, creating a long cold front extending from the 983 mb low to near 30°N, 70°W and westward through the Florida Straits. The system's warm front

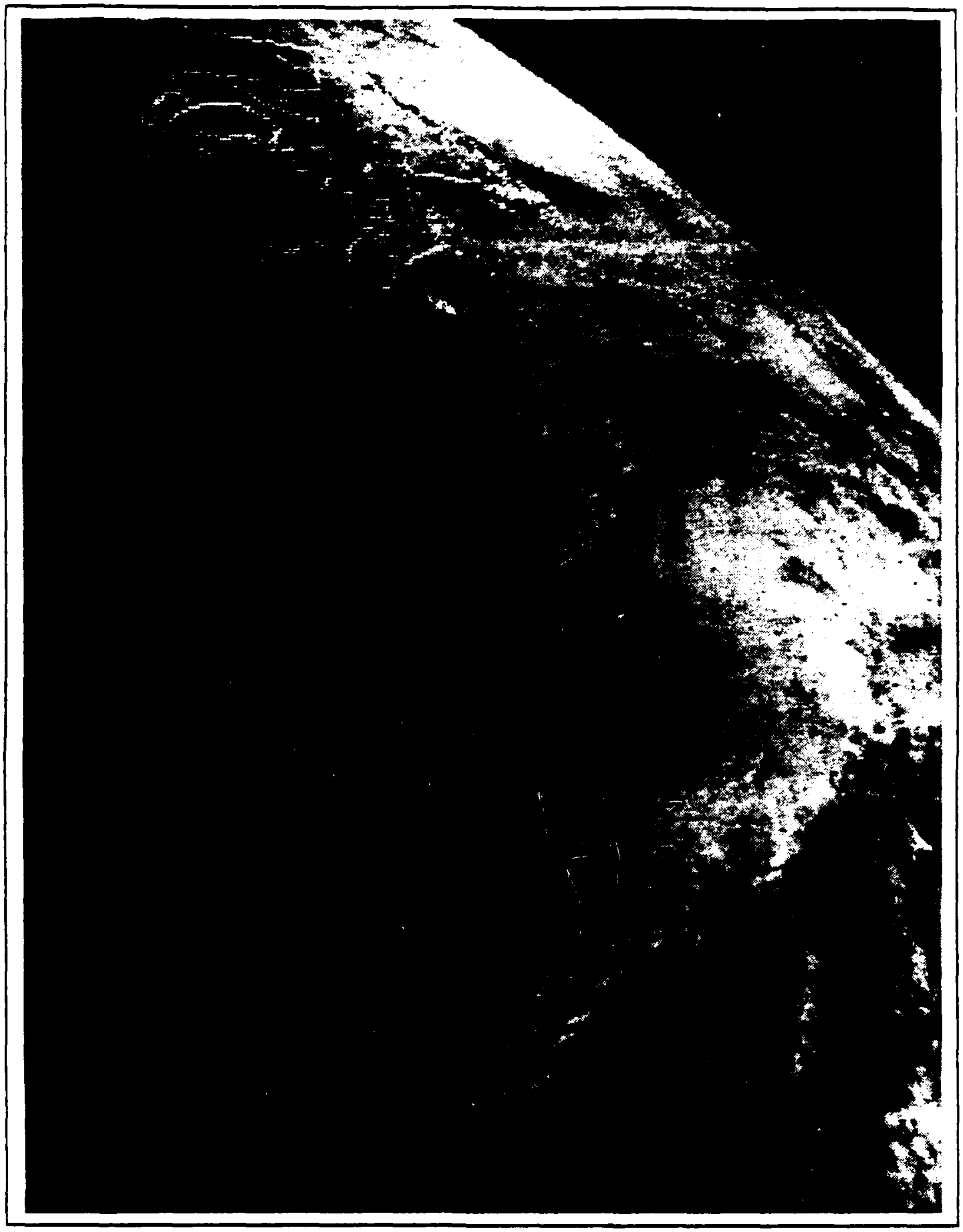

Fig. 8. GOES visual imagery valid 1231 UTC 25 February 1986

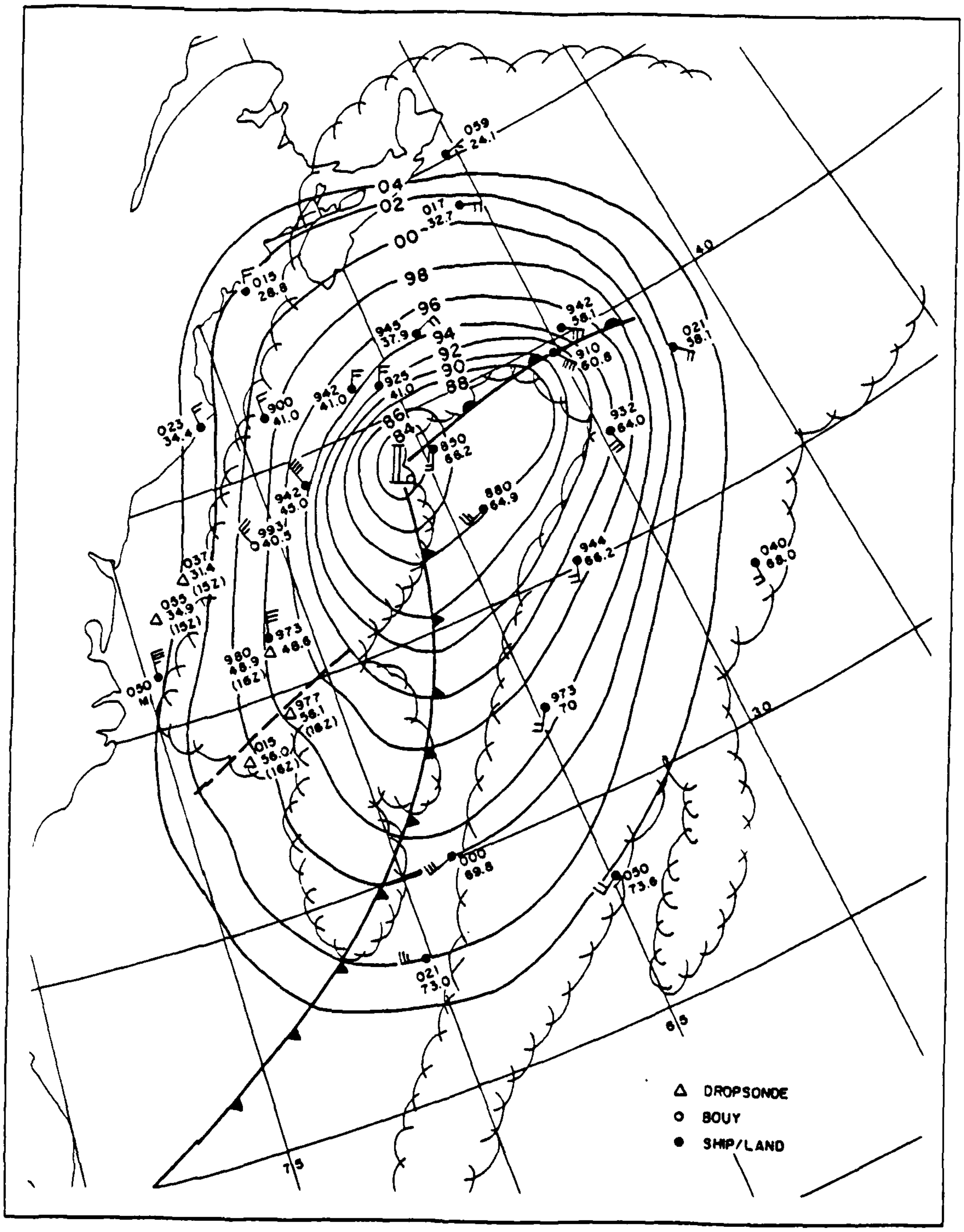

Fig. 9. Same as Fig. 3 valid 1800 UTC 25 February

stretches from the low to near 39°N, 58°W. The southerly winds ahead of the cold front continued to advect warm air northward. Temperatures ranged from 60.8 to 66.2 °F as far north as 40°N.

GOES visual imagery valid at 1830 UTC (Fig. 10) shows the line of cold frontal cloudiness corresponding well with the position of the surface front. However, the clouds along the front to the south of 30°N, 70°W are quite fragmented, with only a thin line of convection denoting the front's position through the Florida Straits. The separation between the front and the old frontal boundary ahead of it is decreasing as the western front accelerates eastward.

E. SURFACE DISCUSSION FOR 0000 UTC 26 FEBRUARY 1986

During the six hours prior to 0000 UTC 26 February, the deeping rate of this major western North Atlantic storm decreased, with only a 2 mb drop in pressure during that time. The surface analysis (Fig. 11) was based solely on ship and buoy reports. The analysis indicates that the surface low was located near 41°N, 63°W, and had a central pressure of 981 mb. The lack of data in the vicinity of the low makes the determination of the central pressure difficult. The ship reported winds of 35 kt southeast of the low, near 39°N, 63°W, indicate the possibility that the pressure may be even lower. The NMC final analysis for this time positions the low near 40°N, 64°W with a central pressure of 982 mb. Very weak troughing off of the North Carolina coast is all that remained of the western low center.

The cold front associated with the system stretches only from the the main low pressure center to near 32°N, 65°W. The old frontal boundary south of that location is undergoing frontolysis as suggested by the temperature across the front of only 2 to 3 °F in the southern region. The warm front extends from the low center to near 43°N, 54°W. Its position was evidenced by a strong temperature gradient, a 30 °F difference over a distance of 5° latitude east of the low, and a distinct wind shift. This gradient is probably stonger at the front, but the lack of data prohibits any direct calculations of the gradient in that region.

Strong winds in the vicinity of the low are also indicative of this storm's intensity. Several observations of 50 kt winds were reported just ahead of the warm front. Winds in the warm sector ranged from 30 to 40 kt, while behind the low, observations of wind speeds ranged from 20 to 35 kt.

The GOES infrared imagery valid at 0031 UTC (Fig. 12) confirms the dissipation of the southern half of the front. South of 30°N the old frontal boundary was marked

Fig. 10. GOES visual imagery valid 1830 UTC 25 February 1986

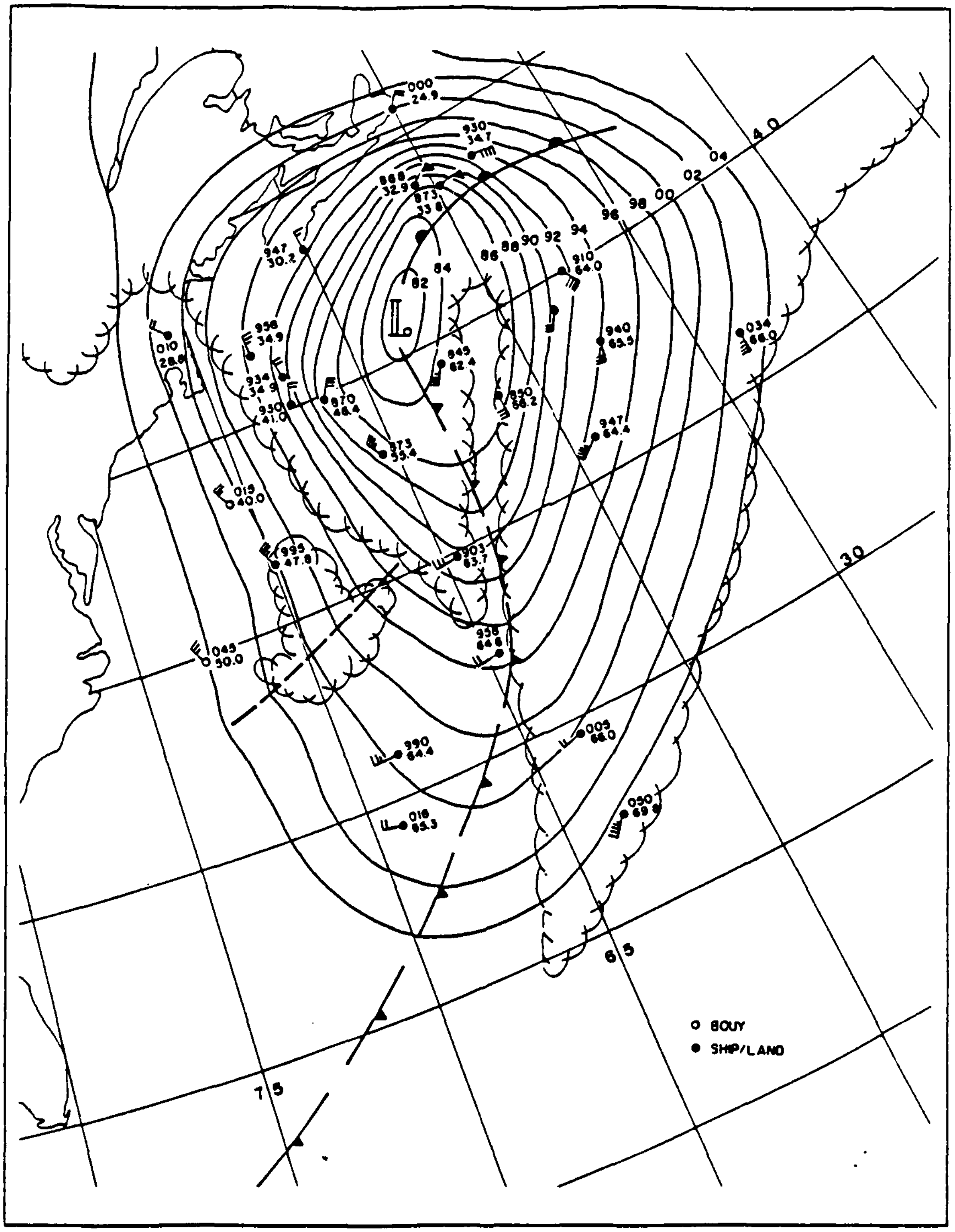

Fig. 11. Same as Fig. 3 valid 0000 UTC 26 February 1986

by a line of fragmented low clouds with no indication of convective activity. North of 30°N the frontal band began to interact with the cloudiness associated with the subtropical flow. Closer to the low center, there continued to be a separation between these clouds of subtropical origin and the clouds associated with the cyclone.

The satellite imagery does indicate an area of vigorous veritical motion north of the low over eastern Nova Scotia. The black area of enhanced cloudiness corresponds to cloud top temperatures less than -60°C , Cloud top temperatures this cold are usually indicative of intense convection.

This cyclone continued to deepen as it moved northward across northern Nova Scotia. At 0600 UTC 26 February the NWS analysis (not shown) indicates the location of the low pressure center south of Nova Scotia, with a central pressure of 973 mb. This value also suggests the 0000 UTC 26 February central pressure of 981 mb may be a high estimate. By 1200 UTC 26 February (Fig. 13), the deepening of the cyclone has slowed dramatically. Now located over northern Nova Scotia, the cyclone has a central pressure of 971 mb. The NORAPS 500 mb analysis valid at 1200 UTC 26 February (not shown) indicates a cutoff circulation over Maine and southwest Nova Scotia, reflecting the maturity of the cyclone and supporting the slower deepening rate. These positions *and strengths are confirmed* by numerous land and ship observations.

F. SUMMARY OF EXPLOSIVE DEEPENING

The surface storm track for the explosively deepening cyclone that developed in the western North Atlantic Ocean is indicated in Fig. 14. The deepening rates at six hour time intervals are presented in Table 1. After moving offshore over South and North Carolina, the storm moved to the northeast over a data sparse ocean region as it deepened from 1005 mb to 981 mb during the first 24 hours of IOP 9. The cyclone continued to deepen another 10 mb during the next 12 hours to 971 mb as it moved across northeastern Novia Scotia. The final storm track exhibits good continuity and hopefully will be useful in future IOP 9 studies.

Fig. 12. EC enhancement of GOES infrared imagery valid 0031 UTC 26 February 1986

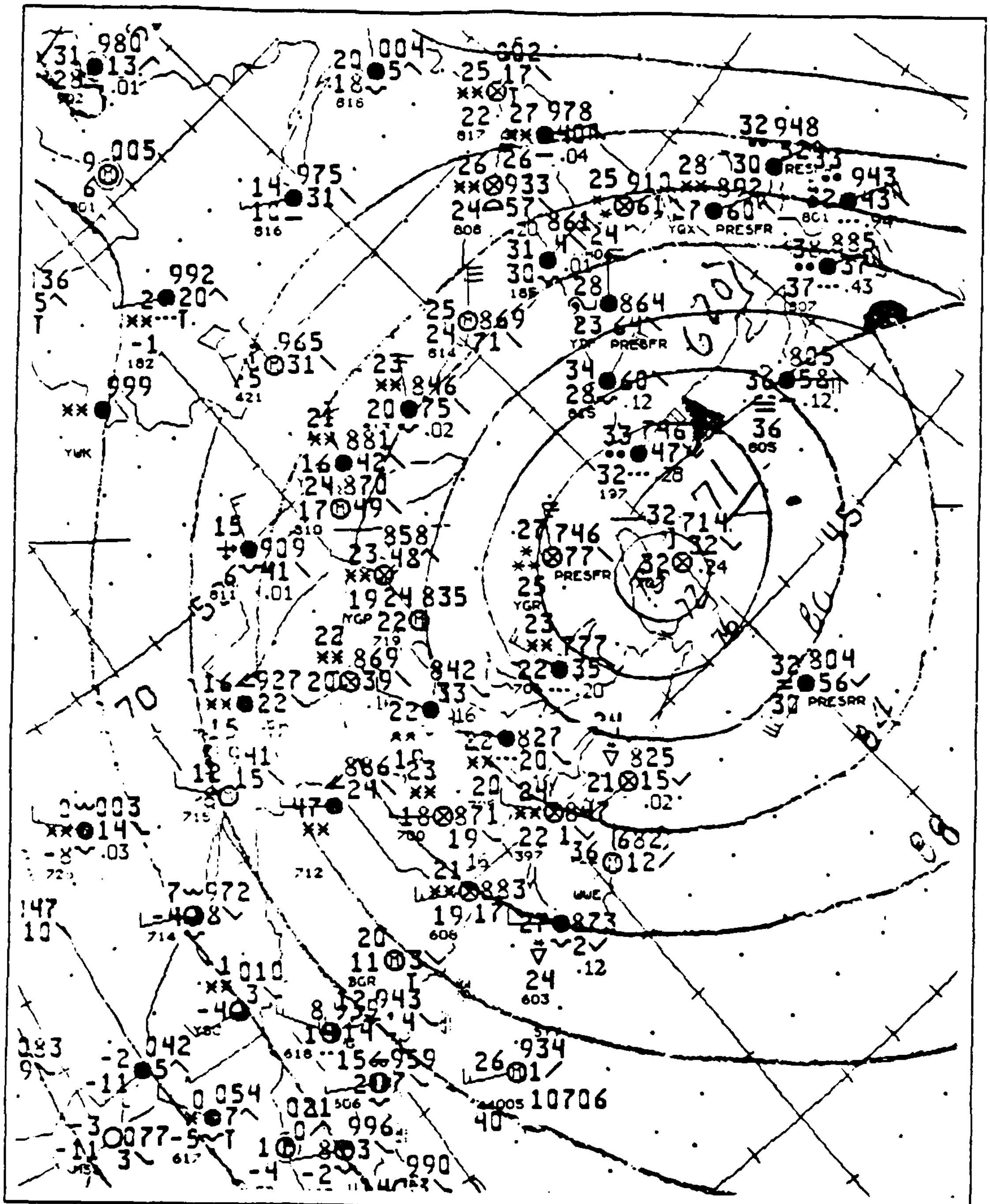

Fig. 13. NWS sea-level pressure analysis (mb) valid 1200 UTC 26 February 1986

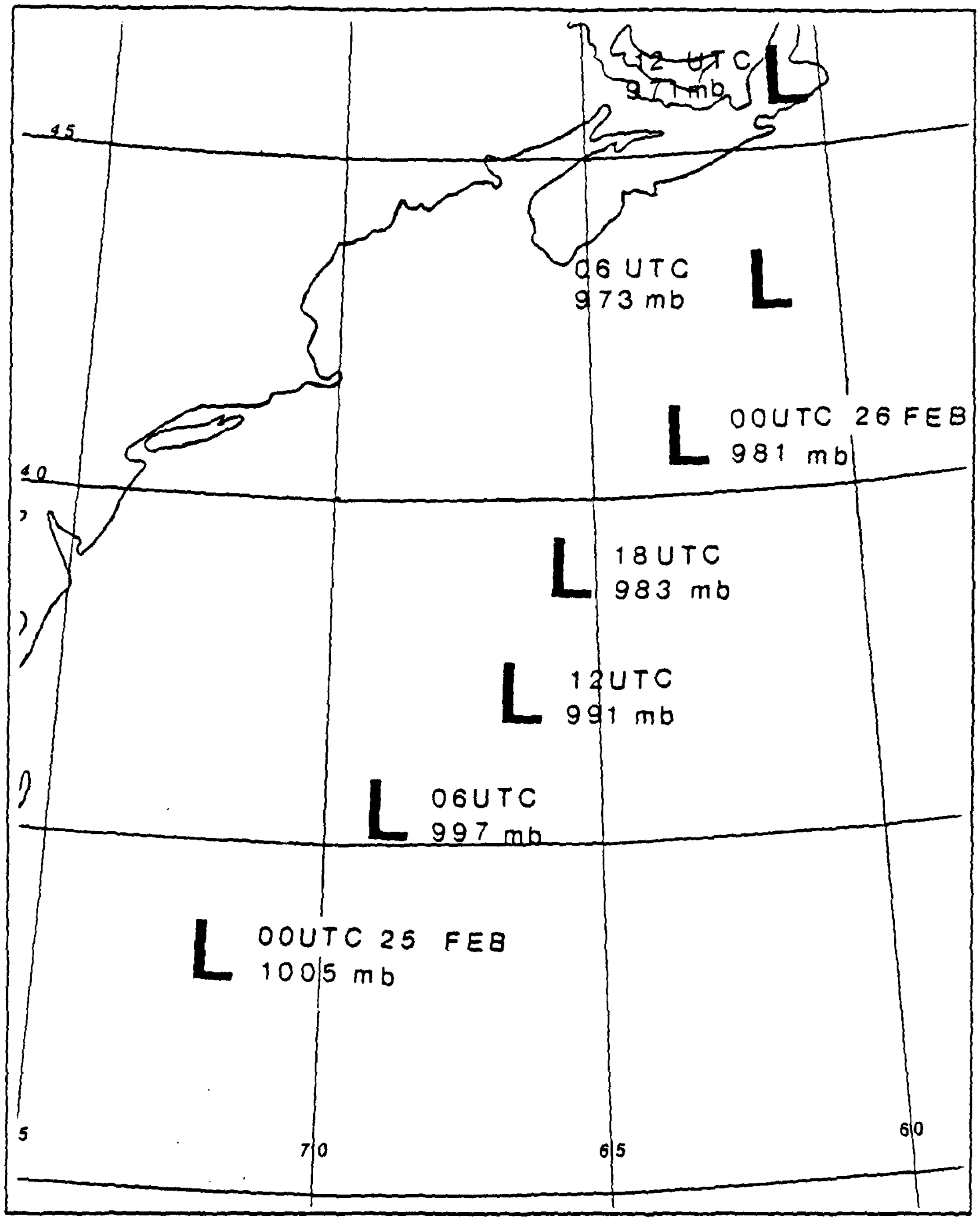

Fig. 14. Surface storm track from 0000 UTC 25 to 1200 UTC 26 February 1986

Table 1 Deepening Rate of IOP 9 Explosive Cyclone			
Day/Time	Central Pressure	Pressure Six Hours Earlier	Deepening Rate
25/0000 UTC	1005 mb	1009 mb	0.7 mb h^{-1}
25/0600 UTC	997 mb	1005 mb	1.3 mb h^{-1}
25/1200 UTC	991 mb	997 mb	1.0 mb h^{-1}
25/1800 UTC	983 mb	991 mb	1.3 mb h^{-1}
26/0000 UTC	981 mb	983 mb	0.3 mb h^{-1}
26/0600 UTC	973 mb	981 mb	1.3 mb h^{-1}
26/1200 UTC	971 mb	973 mb	0.3 mb h^{-1}

G. MODEL FORECAST ERRORS OF THE IOP 9 EXPLOSIVE CYCLOGENESIS

Sanders and Gyakum (1980), Anthes et al. (1983) and others have illustrated the difficulty numerical models experience in forecasting explosive cyclogenesis, frequently underforecasting the surface intensification. This proved to be the case for the IOP 9 explosive cyclogenesis as well. The 36 h mean sea-level pressure forecasts made at 1200 UTC 24 February 1986 by the National Meteorological Center's Limited-Area Fine Mesh Model (LFM), the NMC's Nested-Grid model (NGM), and the Navy's NORAPS model were compared with the surface analysis for 0000 UTC 26 February in Table 2. The 36-hour forecasts and the analysis valid at 1200 UTC 26 February are also included.

All three models forecast some deepening of low center, but none of them forecast the explosive cyclogenesis that occurred. The National Meteorological Center's models covered both error extremes. The LFM forecast a central low pressure of 991 mb, giving in a 10 mb error. The NGM forecast for a low pressure of 1000 mb resulted it an error of 19 mb, while the Navy's NORAPS model forecast of a 994 mb low had a 13 mb error. These errors are conservative estimates since there is evidence that the cyclone was deeper than the 981 mb value. It is interesting to note that the NGM, the newest operational regional forecast model, did not include a full scheme of boundary layer fluxes at this time and had the largest error of the forecasts valid at 0000 UTC 26 February. This fact emphasizes the need for a larger, more accurate data base over the oceans and the need to incorporate boundary layer processes such as vertical heat and moisture

fluxes and better convective parameterizations into the numerical weather prediction models. Both of these processes appear to contribute to explosive cyclogenesis. The lack of data is also evident in the 20 mb errors for the LFM and NGM forecasts valid 1200 UTC 26 February.

Table 2
Regional Model Forecast Errors for
IOP 9 Cyclogenesis

Model	36 Hour Fcst Valid 26/0000 UTC	Sfc Analysis Valid 26/0000 UTC	Error
LFM	991 mb	981 mb	10 mb
NGM	1000 mb	981 mb	19 mb
NORAPS	994 mb	981 mb	13 mb
	36 Hour Fcst Valid 26/1200 UTC	Sfc Analysis Valid 26/1200 UTC	
LFM	991 mb	971 mb	20 mb
NGM	991 mb	971 mb	20 mb

The surface analyses presented indicate that the surface cyclone observed during IOP 9 did deepen explosively over the western North Atlantic. Data input from the GALE project help to verify the explosive deepening and give an indication as to the structure of the storm during its development. The next section examines the structure of the upper levels during IOP 9. Emphasis is placed on features that may have provided upper-level forcing for the surface cyclogenesis.

III. UPPER-LEVEL ANALYSIS DISCUSSION

GALE dropsonde and rawinsonde data proved important in determining the surface positions and intensities of the cyclones during the first 18 hours of IOP 9. These data contributed to upper-level analyses as well. A combination of operationally available rawinsonde data and the data aquired by GALE missions were used to prepare a series of NORAPS upper-air analyses for this case.

The objectives of this chapter is to present the vertical structure of the IOP 9 cyclone using these analyses. The time evolution of 300 mb, 500 mb, 700 mb and 850 mb is described. It was originally planned to compute important diagnostic quantities which may provide insight in this cyclogenesis case. Unfortunately, the objective analyses have not been finished and no diagnostics are available. Before discussing the results of these analyses, a few comments concerning the data processing technique used in the analyses are appropriate.

A. METHODS OF OBJECTIVE ANALYSIS

Fleet Numerical Oceanography Center (FNOC) and the National Meteorological Center (NMC) use two techniques for objective analyses. The NMC's Spectral Model and NGM both use the optimal interpolation technique. The Navy Operational Global Analysis and Prediction System (NOGAPS) also utilizes the optimal interpolation technique, while the operational NORAPS uses the successive corrections method for objective analysis. Both of these techniques convert an irregular field of meteorological data into a set of data grid points available for the model.

Gustavsson (1981) discusses the differences between these two methods of objective analysis. The successive corrections technique is a two dimensional method of creating grid point data. Observations on the same level and in the vicinity of the grid point are statistically combined to obtain a value for the grid point. The observations are weighted by distance so that closer observations have more of an influence in determining the final grid point value. This technique is univariate, meaning that each meteorological parameter calculated for the grid point is calculated independent of other parameters.

The optimal interpolation techinique is a more sophisticated method of determining grid point values. Unlike the distance only "weighting scheme" used in the successive corrections technique, weighting in the optimal interpolation technique depends on the

type of observation, the timeliness of the observation, the data distribution around the grid point and the distance of the observation from the grid point. The optimal interpolation technique is multivariate. Examples of this parameter dependence include the determination of heights hydrostatically from a grid point temperature value and the use of winds to analyze heights (and vice versa).

Using NORAPS, both of these techniques were applied to the data set from IOP 9. At the upper levels, the optimal interpolation technique resulted in analyses that were more dynamically consistant with actual observations. There was also a better vertical consistancy in the analyses when this method was used. As a result, the discussion of the upper-level features evident during IOP 9 is based on NORAPS analyses using the latest results from the optimal interpolation technique.

B. 300 MB DISCUSSION

During this cyclogenesis event, the striking feature at 300 mb is the strong jet streak that develops over the western North Atlantic Ocean. The GALE dropsonde and rawinsonde data help define this wind maximum near the coast, but the lack of data further offshore probably led to an underestimation of the strength of the jet streak at later times of the IOP.

The NORAPS geopotential height and wind analysis valid at 1200 UTC 24 February (Fig. 15) shows a 60 ms^{-1} center exiting the longwave ridge over the western United States and digging into the rear of the east coast long wave trough. This western jet is associated with the surface low pressure center in the Ohio Valley. A second jet streak, indicated by the 50 ms^{-1} isotach, is exiting the base of the trough over northern Florida and southern Georgia. These two jet streaks play an important role in the explosive cyclogenesis that occurred during IOP 9.

The 300 mb absolute vorticity pattern for this time (Fig. 15) shows a large region of positive absolute vorticity ($24x10^{-5}s^{-1}$) over the Ohio Valley due to strong cyclonic shear of the western jet streak. This vorticity maximum, combined with the strong 300 mb flow produces a region of positive vorticity advection (PVA) over eastern Kentucky and Tennessee, the location of the surface development at this time. A second vorticity maximum ($16x10^{-5}s^{-1}$) is located over the coast of South Carolina. Although the vorticity advection associated with this maximum is weak, its existence is possibly related to the formation of the eastern surface low pressure center that developed in the next 12 hours.

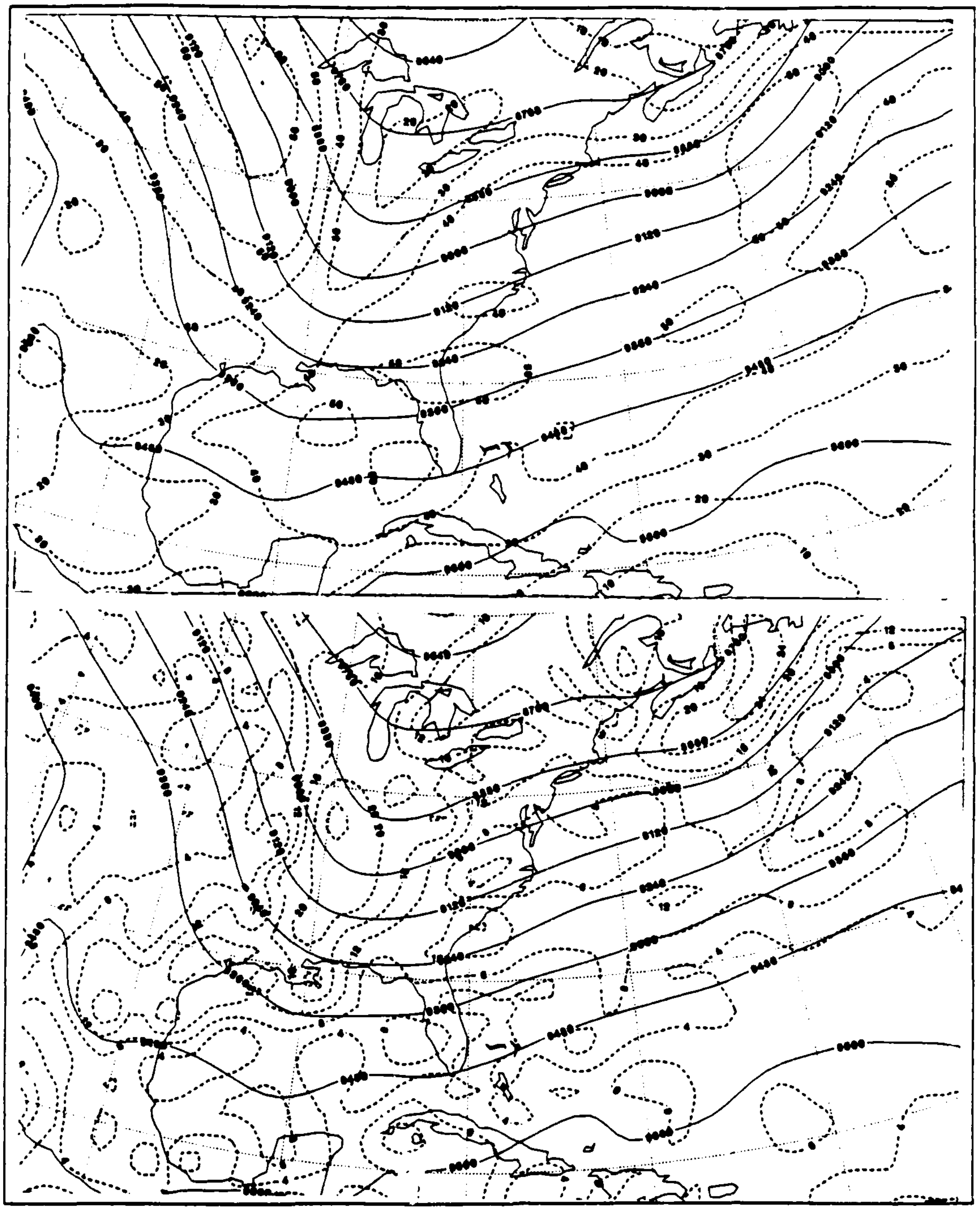

Fig. 15. **300 mb analyses valid 1200 UTC 24 February 1986:** Heights (m) and wind (ms^{-1}) analysis (top) and heights (m) and absolute vorticity ($10^{-5}s^{-1}$) analysis (bottom)

At 0000 UTC 25 February (Fig. 16) the western jet streak, indicated by the 60 ms^{-1} isotach over the Northern Plains and Mississippi Valley continues to dig toward the base of the trough. The jet streak over the western North Atlantic Ocean has become stronger and more organized, and extends from 35°N, 64°W, westward across central Florida to the eastern Gulf of Mexico. This wind maximum is supported by rawinsonde data from the Cape Hatteras (RVC), which reported 110 kt near 300 mb.

The 300 mb absolute vorticity pattern for this time (Fig. 16) indicates a vorticity maximum of $20 \times 10^{-5} s^{-1}$ over the midwestern United States. This positive vorticity is associated with the wind shear caused by the jet streak in the region, but less vorticity advection is evident compared to 12 hours earlier. Meanwhile, the vorticity maximum ($20 \times 10^{-5} s^{-1}$) over North and South Carolina has strengthened and increased in size. The area of PVA off the Carolina coast corresponds nicely with the surface low positions and associated cloudiness.

The 300 mb geopotential height and wind field analysis valid at 1200 UTC 25 February (Fig. 17) indicates that a portion of the western jet streak is moving through the base of the trough and is now influencing the surface cyclogenesis off the Carolina coast. This jet streak, as indicated by the 60 ms^{-1} isotach, extends from 30°N, 75°W westward through the Florida panhandle. The maximum wind contour of 60 ms^{-1} is supported by several dropsonde reports in that region of winds from 90 to 95 kt at 400 mb. Had data been available for locations further east, this 60 ms^{-1} core would probably been elongated even more. This supposition is based on the explosive development of the eastern surface low.

The 300 mb absolute vorticity pattern for this time (Fig. 17) indicates an extremely strong area of positive vorticity over northern Florida and southern Georgia. This region, with a maximum vorticity contour of $32 \times 10^{-5} s^{-1}$ combined with the strong 300 mb flow, creates a PVA area stretching from the coast to near 73°W. This region agrees well with the position of western surface low. A second relative vorticity maximum is located in the vicinity of the eastern surface low center near 37°N, 65°W. Again, had more upper-level data been acquired in that region, the calculated vorticity may have been stronger than $16 \times 10^{-5} s^{-1}$.

At 0000 UTC 26 February (Fig. 18) the core of the jet streak, as indicated by the 60 ms^{-1} isotach exiting the base of the trough, extends from near 28°N, 75°W northeastward to 33°N, 68°W. A second 60 ms^{-1} jet core, associated with the explosively

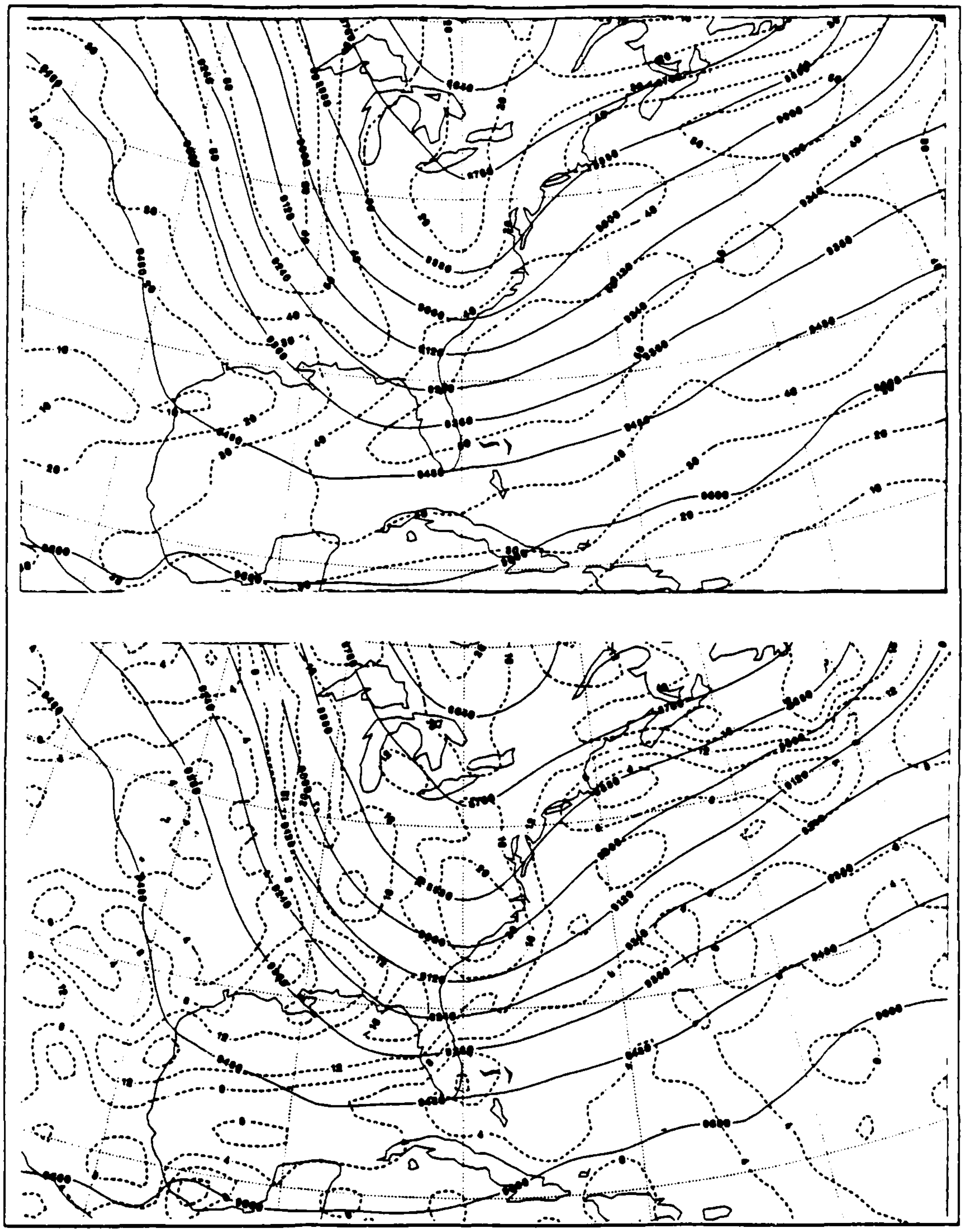

Fig. 16. Same as Fig. 15 valid 0000 UTC 25 February 1986

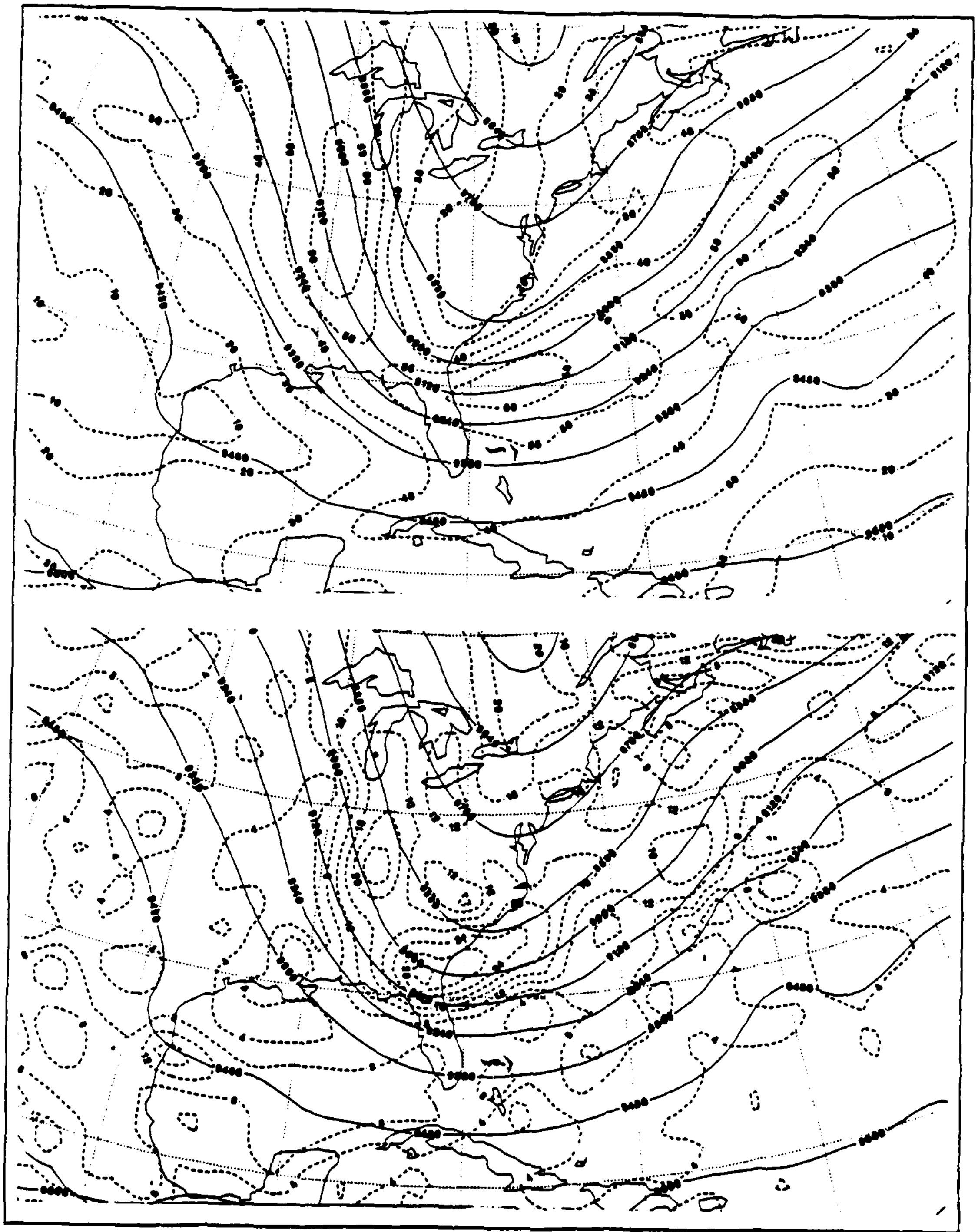

Fig. 17. Same as Fig. 15 valid 1200 UTC 25 February 1986

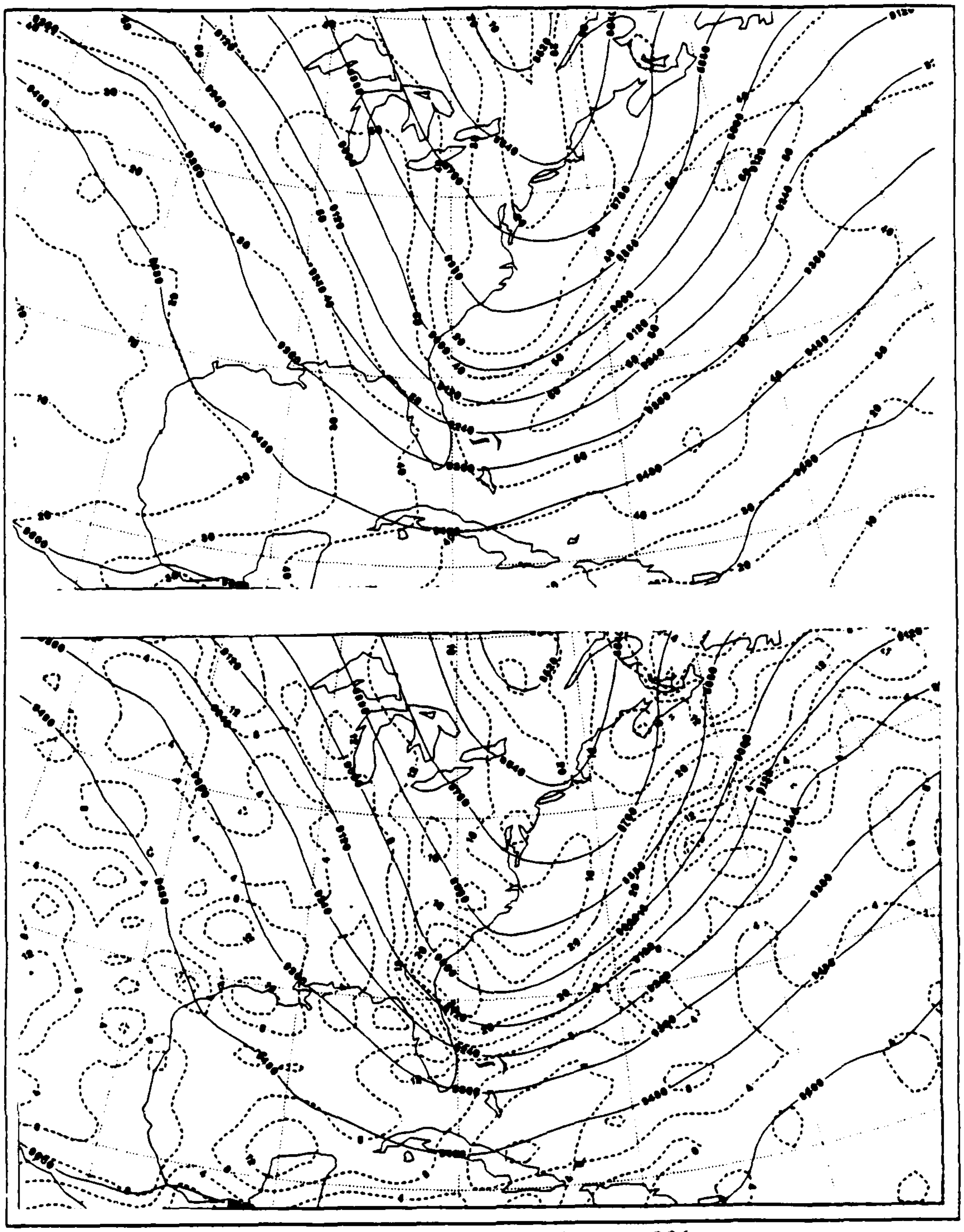

Fig. 18. Same as Fig. 15 valid 0000 UTC 26 February 1986

deepening suface cyclone, is located near 40.0°N, 60.0°W. The discontinuous maximum wind band is probably due to the lack of upper-level data.

The absolute vorticity pattern for this time (Fig. 18) shows an area of positive vorticity ($24 \times 10^{-5} s^{-1}$) centered over the Georgia and South Carolina coasts. There is little PVA associated with this maximum. The lack of PVA near the coast is in agreement with the dissipation of the western low pressure center. The largest area of PVA in the western North Atlantic is associated with the explosively deepening cyclone. A $20 \times 10^{-5} s^{-1}$ vorticity maximum is centered near 37.0°N, 64.0°W, with an area of PVA to the northeast. This PVA region spreads over the position of the rapidly deepening suface low pressure center.

The intensification of the 300 mb jet streak and the creation of positive vorticity advection over the western North Atlantic Ocean are significant features that influence the development of the surface cyclone. Although the intensities of these features are probably underestimated due to a lack of data, the observation of a strong jet streak and PVA region may offer a partial explanation for the explosive nature of the cyclogenesis.

C. 500 MB DISCUSSION

The NORAPS 500 mb geopotential height analyses track the eastward movement of the long wave trough across the eastern United States. Vorticity patterns show significant areas of PVA associated with the surface cyclogenesis, particularly near the coast of North and South Carolina. Very little temperature advection at 500 mb is evident over the region of surface cyclogenesis.

At 1200 UTC 24 February (Fig. 19) a broad long wave trough covers the eastern United States. A short wave moving across the Ohio Valley extends from eastern Michigan, south through Mississippi, and into the Gulf of Mexico. An absolute vorticity maximum of $16 \times 10^{-5} s^{-1}$ is located over the Midwest, with a small area of PVA extending over central Kentucky, the location of the surface center. The temperature analysis (not shown) indicates no significant temperature advection at this time.

The 500 mb geopotential heights and vorticity analysis valid at 0000 UTC 25 February (Fig. 19) shows that the shortwave has continued to move toward the east, extending from western Pennsylvania, southward through northern Florida and into the eastern Gulf of Mexico. The vorticity associated with this short wave has remained constant and is now centered over North and South Carolina. A weak area of PVA is evident off the coast of the Carolinas in good agreement with the positions of the surface

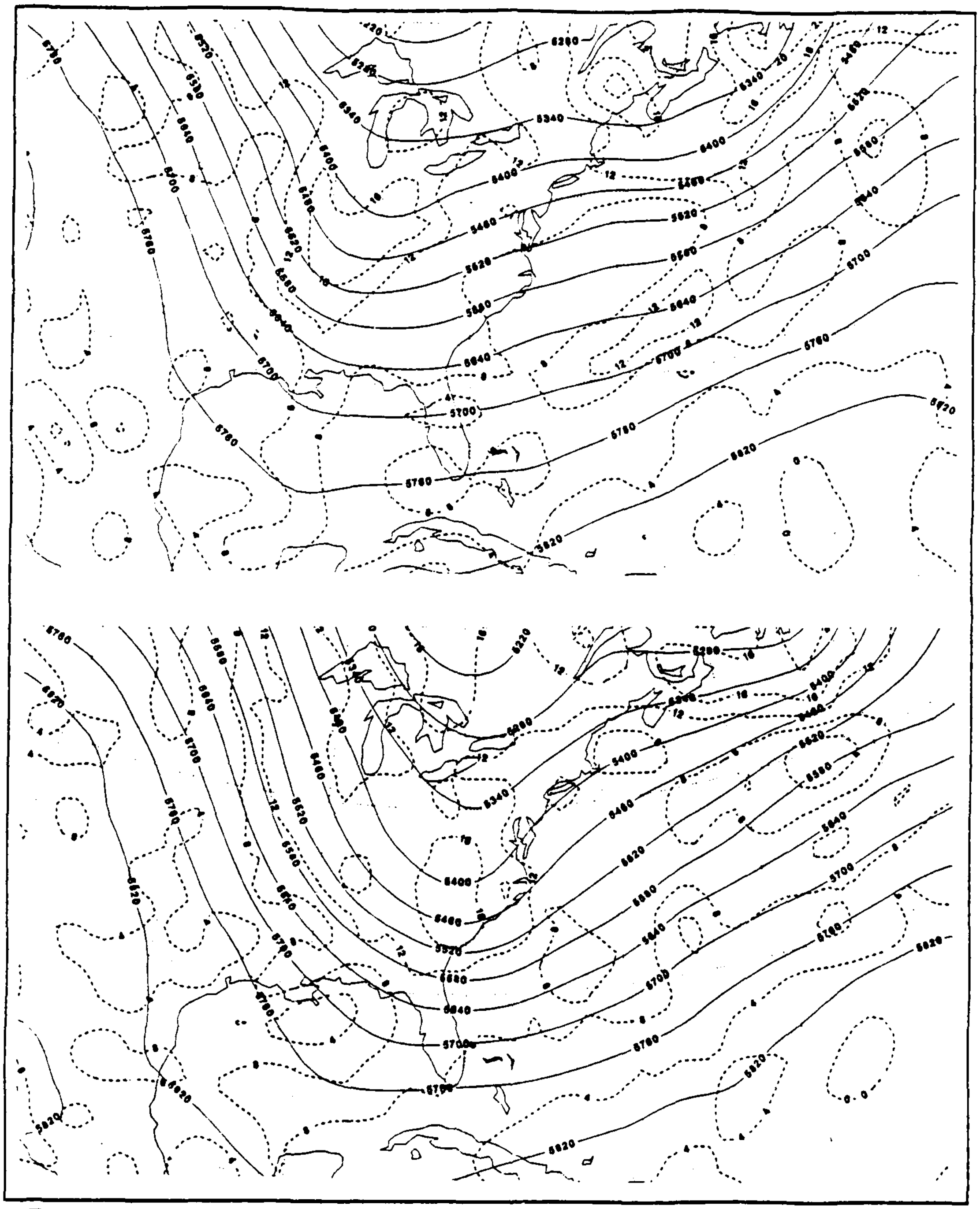

Fig. 19. 500 mb analyses valid 1200 UTC 24 and 0000 UTC 25 February 1986: Heights (m) and absolute vorticity ($10^{-5}s^{-1}$) analysis for 1200 UTC 24 (top) and 0000 UTC 25 (bottom) February 1986

lows at this time. Again, there is no significant temperature advection at the 500 mb level.

By 1200 UTC 25 February (Fig. 20) the trough has moved offshore, extending from east of Lake Ontario, southward along the eastern seaboard to southern Florida. The vorticity maximum has strengthened, with a small $24x10^{-5}s^{-1}$ center over northern Florida. This increase in vorticity is due to the shear vorticity created by the formation of a 40 ms^{-1} jet streak over northern Florida. A vorticity lobe ($12x10^{-5}s^{-1}$) extends from this maximum over Florida to near 38°N, 65°W. This lobe corresponds well with the location of the eastern low pressure center. Again, the lack of upper-level data may result in rather weak support for the explosively deepening cyclone further east.

The short wave trough continues to move offshore, and by 0000 UTC 26 February (Fig. 20) extends from Cape Cod southward to near 25°N, 72°W. The main vorticity center has weakened slightly to $20x10^{-5}s^{-1}$ and has remained over northern Florida and southern Georgia with the main long wave trough. The vorticity lobe supporting the eastern low pressure center 12 hours earlier is not evident at this time. The temperature analysis (not shown) shows a large area of cold advection from the trough axis westward to the coast.

D. 700 MB DISCUSSION

The NORAPS 700 mb heights and temperature analyses during the first 24 hours of IOP 9 give some indication that the trough over the eastern United States is deepening. At 1200 UTC 24 February (Fig. 21) the shortwave trough extends from western Ohio southward through central Alabama. There is a hint of cold advection behind the trough, but it is extremely weak.

At 0000 UTC 25 February (Fig. 21) the trough stretches from central Pennsylvania southward off the coast of South Carolina and back into northern Florida. Although not strong, some cold air advection is evident behind the trough. This increase of cold advection into the base of the trough will deepen the trough aloft and enhance the potential cyclogenesis.

The 700 mb cold advection continues to increase as the surface cyclone develops. By 1200 UTC 25 February (Fig. 22) the trough is offshore, extending from just south of Long Island to northeastern Cuba. Strong cold advection can be seen over eastern Maryland, Virginia and North Carolina associated with the rapid cyclogenesis. There is a small region of warm advection along 60°W between 35°N and 42°N. This warm advection is in the general vicinity of the surface warm front position at this time.

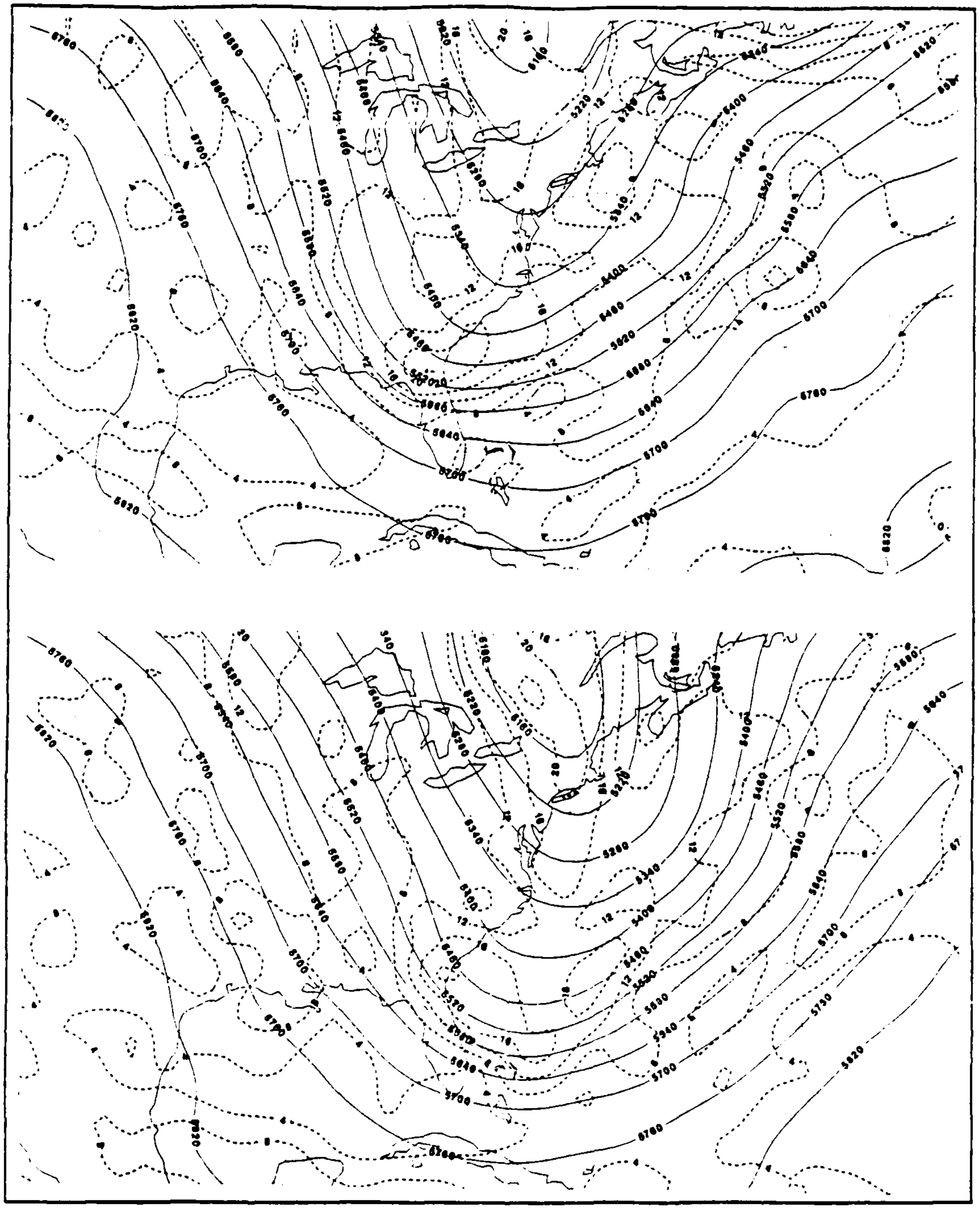

Fig. 20. Same as Fig. 19 valid 1200 UTC 25 (top) and 0000 UTC 26 (bottom) February 1986

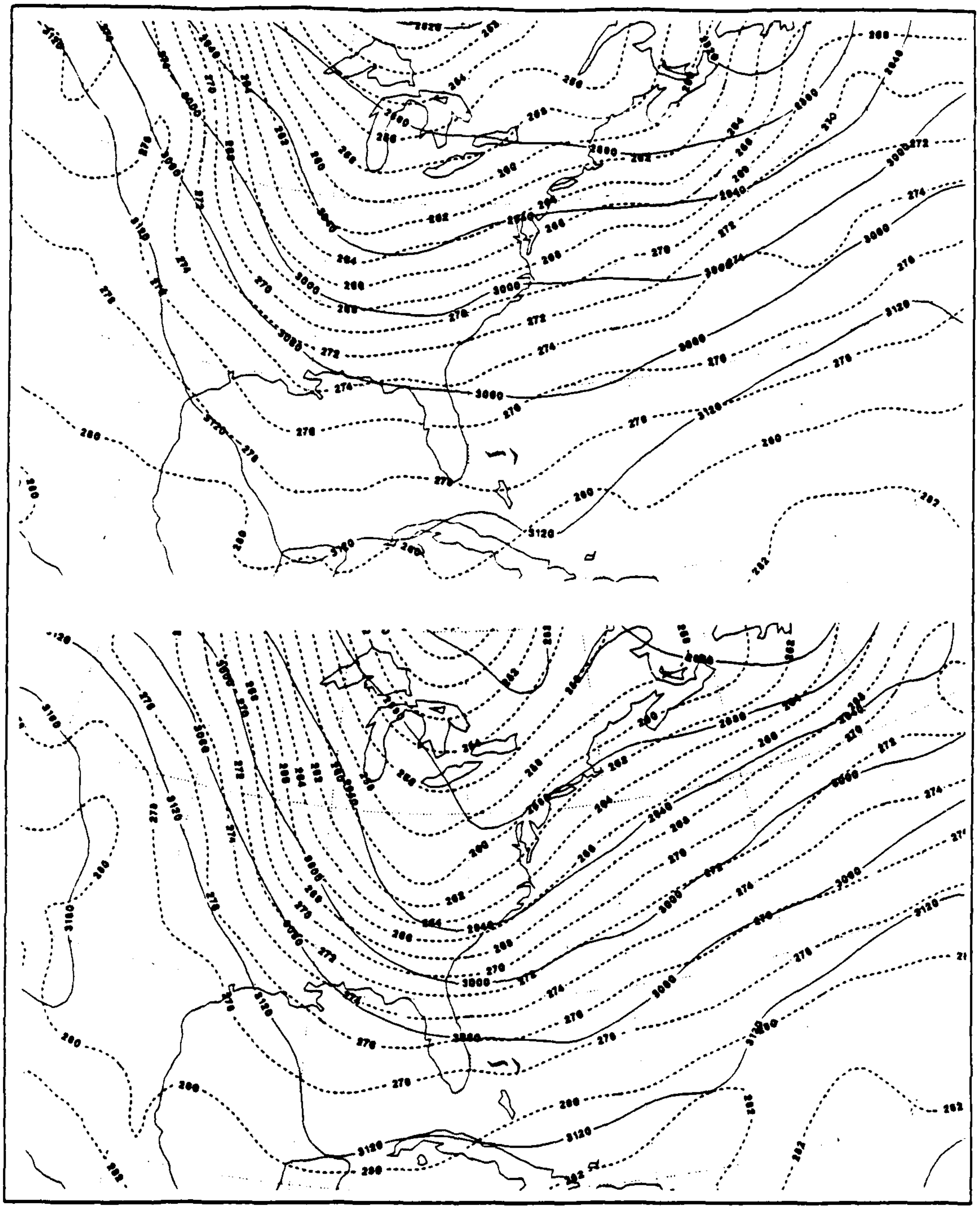

Fig. 21. 700 mb analyses valid 1200 UTC 24 and 0000 UTC 25 February 1986: Heights (m) and temperature (K) analysis for 1200 UTC 24 (top) and 0000 UTC 25 (bottom) February 1986.

By 0000 UTC 26 February (Fig. 22) the trough extends from southwest of Nova Scotia southward to 30°N, 69°W and then southwestward to near 25°N, 73°W. A large region of cold advection has developed behind the trough, associated with the flow around the surface cyclone. An area of warm advection north of 40°N between 50°W and 60°W is also evident. Again this warm advection pattern corresponds well with the position of the surface warm front.

E. 850 MB DISCUSSION

The development of strong cold advection behind the trough is also analyzed by NORAPS at 850 mb. The geopotential heights and temperature analysis valid 1200 UTC 24 February (Fig. 23) shows a closed 1410 m height contour over the Ohio Valley. This closed circulation is associated with the sea-level low pressure center over eastern Kentucky. A trough extends from this circulation to the southwest through western Tennessee, southern Arkansas and northeastern Texas. A large area of cold advection covers most of the Midwest, giving the first indication of short wave amplification.

At 0000 UTC 25 February (Fig. 23) the closed circulation is no longer visible as the surface system becomes disorganized as it moves across the Appalachain Mountains. However, the trough has amplified considerably with 1410 m heights at 850 mb over South Carolina. The trough now stretches from eastern New York southward along the eastern seaboard through central Florida. An area of extremely strong cold advection covers the southeastern United States.

The rapid deepening of this 850 mb trough continues and by 1200 UTC 25 February (Fig. 24) a 1320 m closed height contour is analyzed over the western North Atlantic Ocean. The position of this center corresponds well with the positions of the two surface low pressure centers. The elongated shape of the 850 mb circulation resembles the "double low" surface configuration. The trough has moved offshore and extends from near 35°N, 73°W southward through southern Florida. The region of strong cold advection is evident behind the trough over most of the east coast states and the adjacent ocean region. Below freezing temperatures are found as far south as southern South Carolina. The extent of the cold air is apparent in the visible satellite imagery from this time (Fig. 8) as cloud streets and open celled cumulus formed over the Carolinas and the ocean region behind the trough. Warm advection to the northeast of the circulation corresponds with the position of the surface warm front.

At 0000 UTC 26 February (Fig. 24) the trough extends from near 36.0°N, 65.0°N to the southwest through northwestern Cuba. The region of the cold advection has

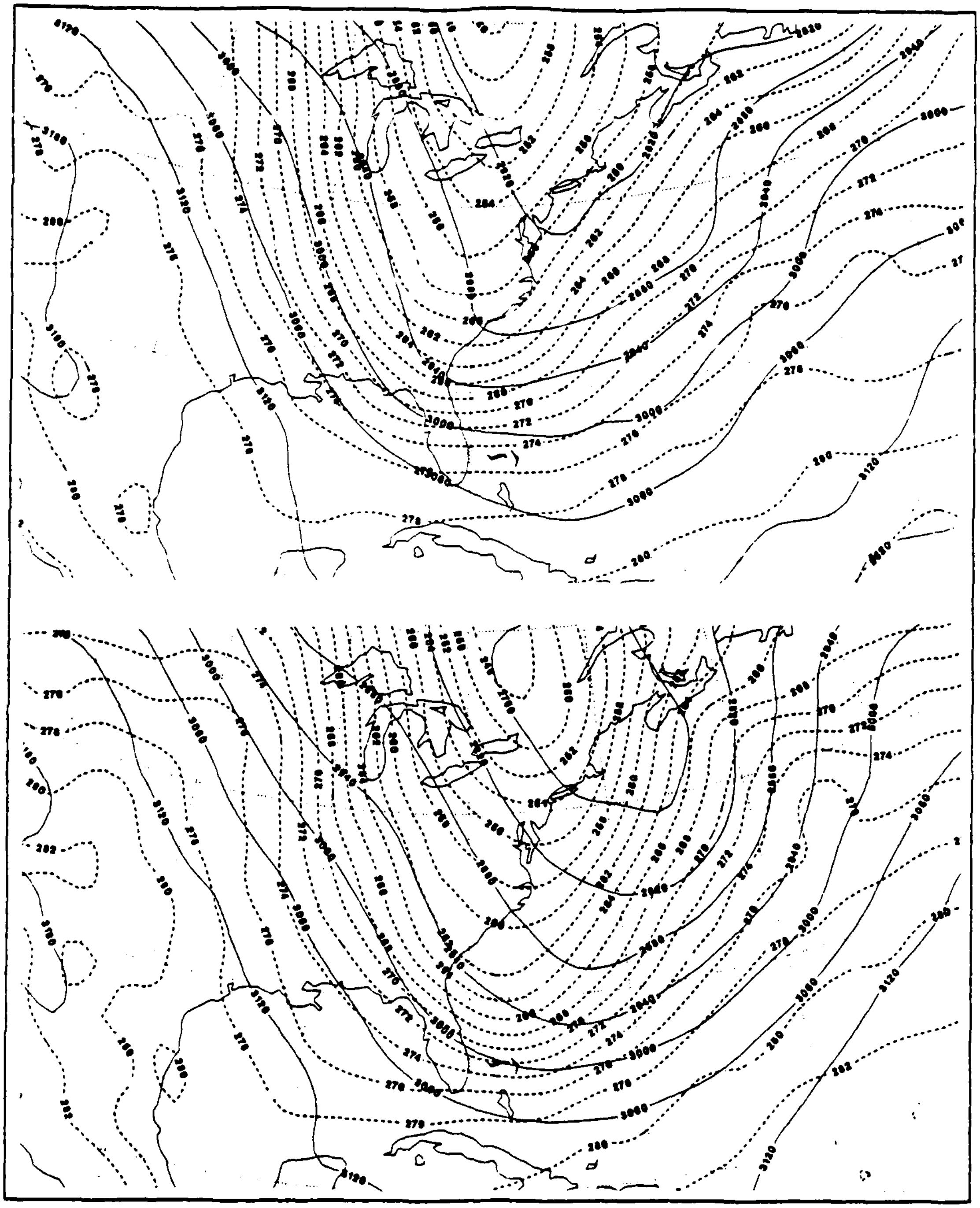

Fig. 22. **Same as Fig. 21 valid 1200 UTC 25 (top) and 0000 UTC 26 (bottom) February 1986**

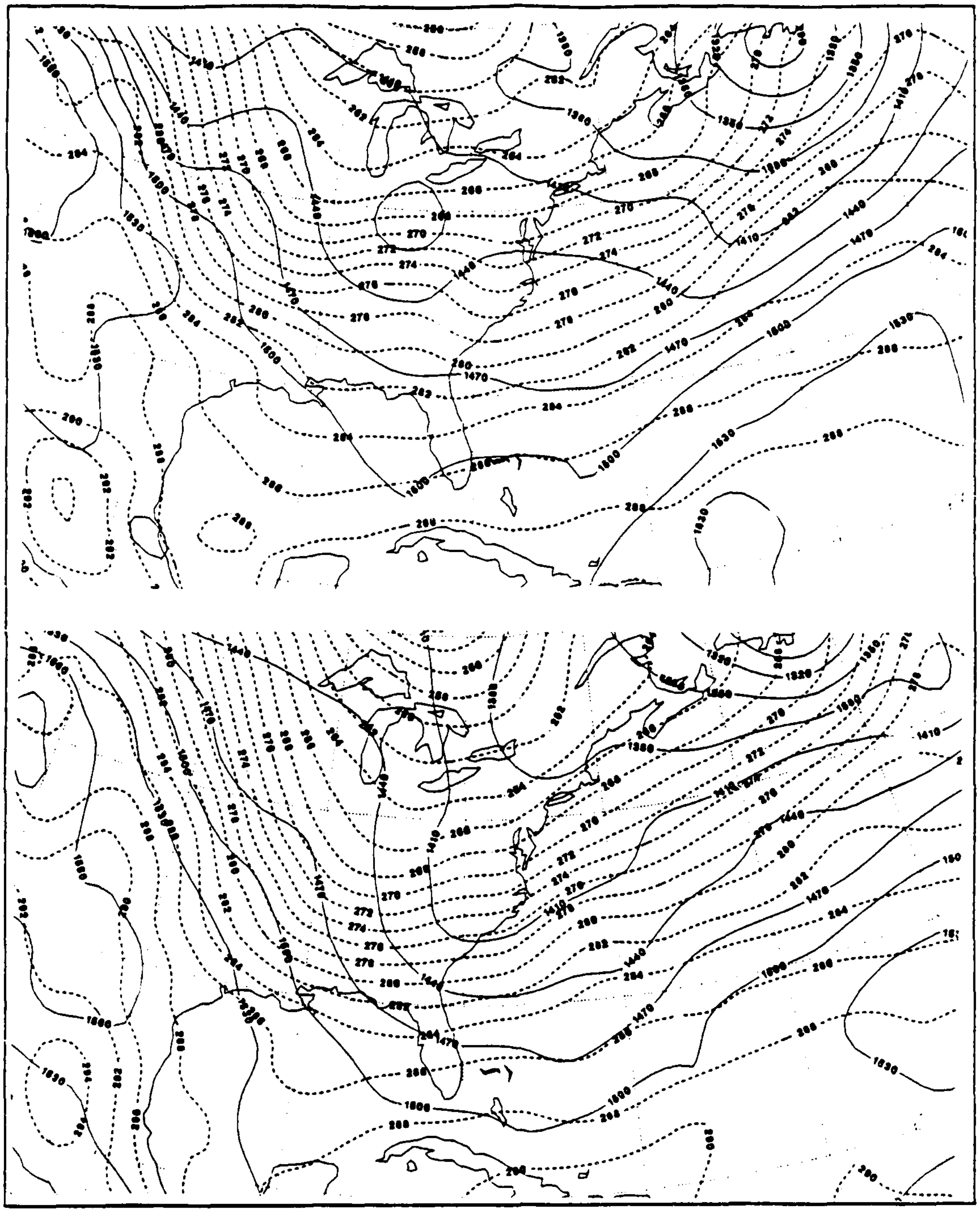

Fig. 23. **850 mb analyses valid 1200 UTC 24 and 0000 UTC 25 February 1986:** Heights (m) and temperature (K) analysis valid 1200 UTC 24 (top) and 0000 UTC 25 February 1986 (bottom)

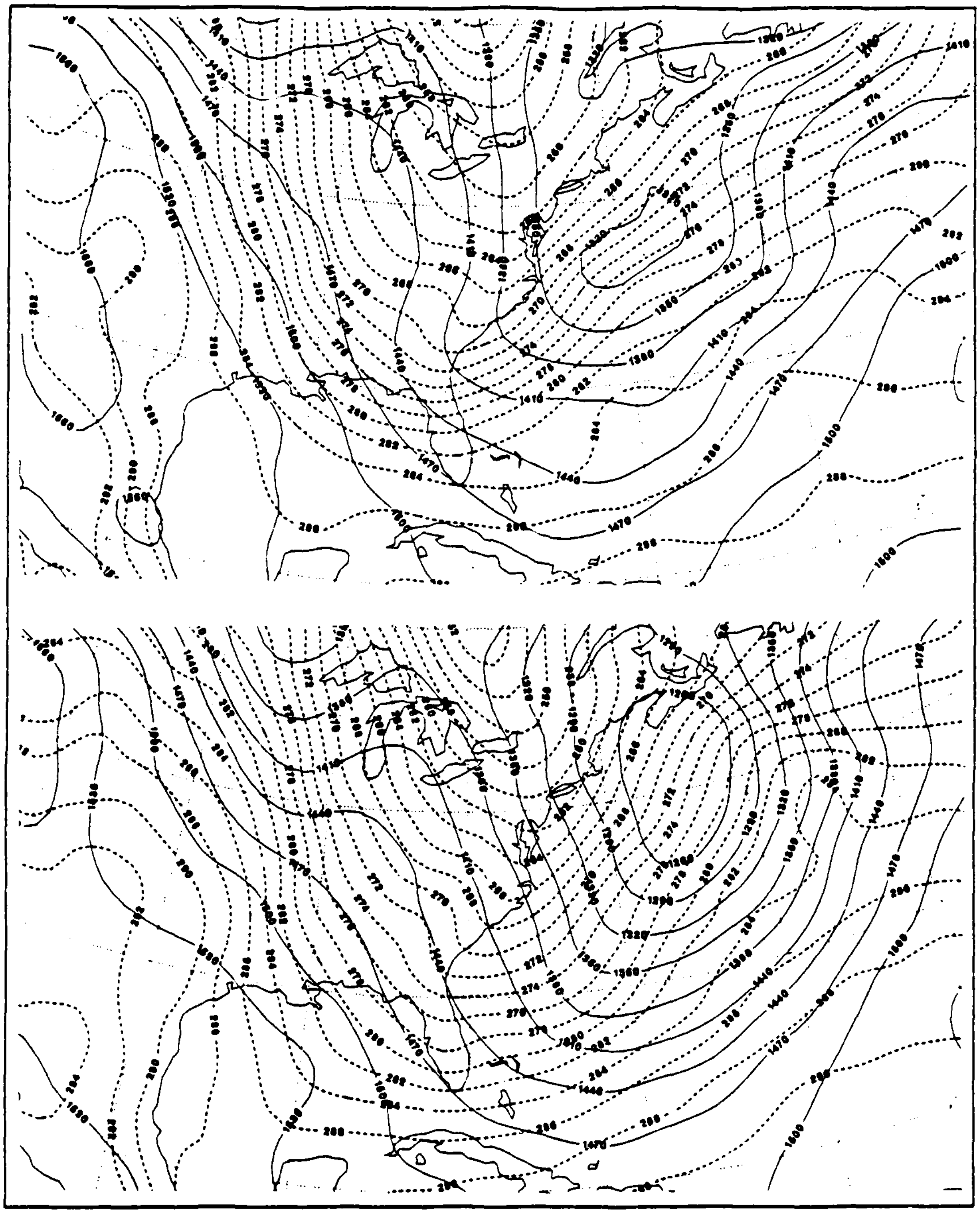

Fig. 24. Same as Fig. 23 valid 1200 UTC 25 (top) and 0000 UTC 26 February 1986 (bottom)

continued to spread over the western North Atlantic Ocean, reenforcing the surface cyclone development. Again, the area of warm advection matches the surface warm front position reasonably well.

F. SUMMARY OF UPPER-LEVEL ANALYSES

The NORAPS upper-level analyses provide additional information to describe the explosive cyclogenesis that occurred during IOP 9. Cold temperature advection at 700 and 850 mb, particularly during the earlier times of IOP 9 , indicate that the upper-level trough over the eastern United States was deepening. The development of a strong 300 mb jet streak and positive vorticity advection at 300 mb and 500 mb appear to be related to the surface development. The secondary ageostrophic circulation associated with the jet streak structure may have provided some additional vertical motion necessary for the development of the cyclone.

In general, the upper-level analyses tended to support surface cyclogenesis. The westward tilt with height of the system was apparant at all levels and times, and the upper-level structure was consistent with the positions of the cyclones at the surface. The location of the PVA regions and important temperature advection patterns matched the surface cyclone movement and frontal features.

Despite the positive indications for cyclogenesis evident in the upper-level analyses, the inclusion of the additional GALE data only helped complete a "thumbnail sketch" of the upper levels during IOP 9. The lack of data over the ocean, particularly in the vicinity of the eastern surface low pressure center, resulted in the underestimation of the winds and vorticity patterns in that region. The analyses over that region give only modest indications of the surface development, and they do not fully indicate the explosive nature of the cyclone. Additional objective analysis studies are required to improve these analyses for IOP 9.

IV. THE ENVIRONMENT OF THE SURFACE CYCLONES

Gyakum (1983 a,b) and Pertle (1987) point out that mesoscale processes play a significant part in rapid cyclogenesis. A main goal of GALE (GALE Field Program Summary, 1986) was to acquire data to study the environment conducive to explosive cyclogenesis events. To achieve this goal, numerous dropsonde and rawinsondes were launched in the vicinity of the two low pressure centers over the western North Atlantic Ocean.

As discussed previously, the wind and pressure information from the dropsonde and rawinsonde data help confirm the existence of two separate low pressure centers at the beginning of IOP 9 and show the eastern low center becoming the dominant system. The observations also help provide an accurate description of moisture, thermal and stability characteristics near the cyclones during the first 12 hours of the IOP. The objective of this chapter is to explore the detailed information that can be gathered from the dropsonde observations.

A. 0000 UTC 25 FEBRUARY 1986

The locations of the dropsondes launched during the first half of the NOAA Citation dropsonde mission, which lasted from 2130 UTC 24 February to 0800 UTC 25 February, are shown in Fig. 25 relative to the surface positions of the low pressure centers at 0000 UTC 25 February. The position of the Cape Hatteras (RVC), which launched a rawinsonde at 0000 UTC, is also shown. Most of these observations were concentrated around the western low center, with two observations taken between the low centers. Very little information is available from the vicinity of the eastern low.

Vertical temperature and wind profiles for D003 and D234 are plotted in Fig. 26. The data from D003, located northeast of the western low pressure center, indicates a relatively moist, unstable environment, particularly at the lower levels. A very moist layer extends from the surface to 700 mb. The Showalter Stability Index (SSI) for this location is 0, indicating weak instability. Both of these features are evident in the satellite imagery (Fig. 4), as broken low-level cloudiness and convective cells can be seen in this region. The dropsonde wind directions at D003 veer with height, indicating warm air advection at lower levels of the environment. The rapid increase of wind speeds with height is also significant. Reports of 80 kt winds at 500 mb and 90 kt winds at 400 mb support the strong jet streak evident on the NORAPS upper-air analysis.

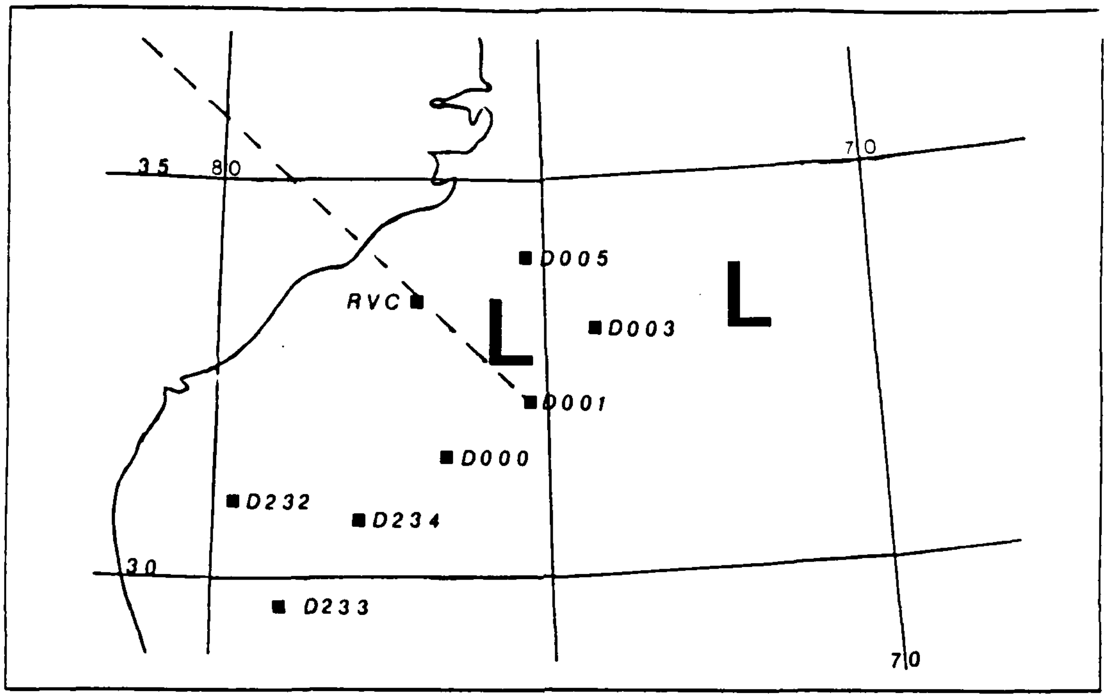

Fig. 25. Citation dropsonde locations for 0000 UTC 25 February 1986: Citation dropsonde and Cape Hatteras rawinsonde locations relative to the sea-level low pressure center positions

The sounding from D234, located southwest of the western low pressure center, depicts a significantly different environment. The most dramatic feature of this profile is the subsidence that extends to 850 mb. The warming associated with the subsidence is seen at all levels. For example, the observed 700 mb temperature at D234 of -1.7°C is almost 3°C warmer than the 700 mb temperature at D003. This warming increases the stability of the region and is reflected in a SSI value of +5, which indicates only weak instability. There is no directional wind shear with height at D234, with westerly winds reported at all levels. This indicates neutral temperature advection in the region southwest of the western low. Maximum wind speed in this region are slower than those northeast of the low, with reports of only 75 kt winds at 400 mb. The location of this dropsonde is south of the main jet core.

Another tool available to study the environment over the western North Atlantic Ocean is the vertical cross-section. The cross-section valid at at 0000 UTC 25 February (Fig. 28) runs from the northwest to the southeast through Dayton (DAY), Huntington (HTS), Greensboro (GSO), Wilmington (ILM), Cape Hatteras (RVC) and D001 (see

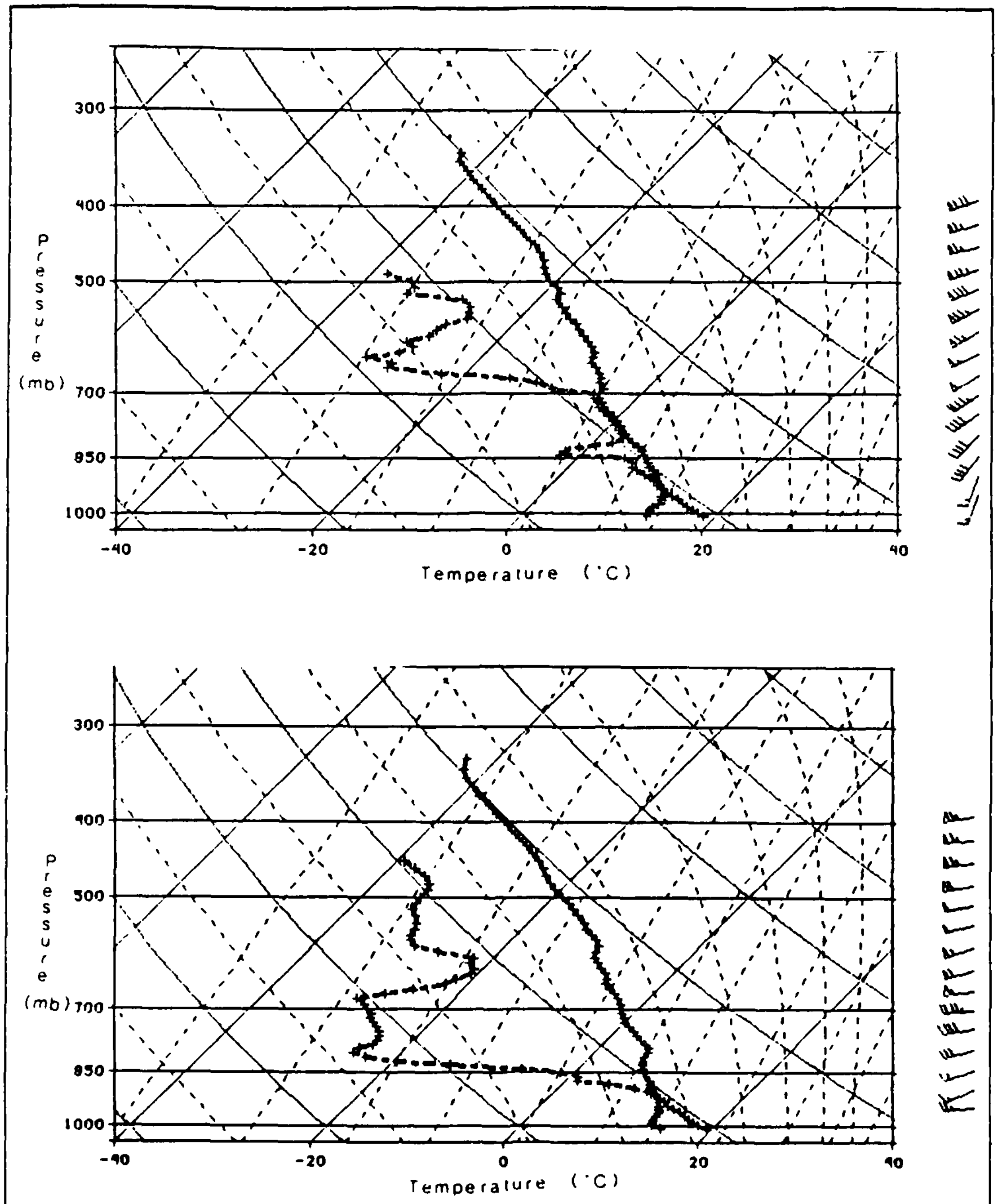

Fig. 26. Citation dropsonde soundings for 0000 UTC 25 February 1986: D003 (top) and D234 (bottom). See Fig. 25 for dropsonde locations

dashed line in Fig. 25). Several important features are evident in this cross-section. First, there is the shift of the isentropes (lines of constant potential temperature) from the near horizontal structure analyzed between Greensboro and Wilmington to the nearly veritical orientation between the Cape Hatteras and D001. The motion of air parcels tend to follow the slope of the isentropes (Wallace and Hobbs, 1977), so the vertical isentropes off the coast of North and South Carolina indicate an unstable boundary layer. The dry adiabatic lapse rate found in the lowest levels of soundings D003 and D234 also indicate this structure. Located to the southwest of the rapidly deepening low pressure center, this region of instability seems out of place. The southwest quadrant of a developing cyclone is usually characterized by subsidence and cold advection, both tend to stabilize the environment. However, over the western North Atlantic Ocean, this instability is the result of the warming of the lowest layer of cold air flowing off the continent by the warm water of the Gulf Stream. The existence of an elongated trough rather than two separate low pressure centers may be another cause for this region of instability.

Other features easily detected on the cross-section include the upper-level baroclinic zone east of Greensboro and extending southeast of D001. This feature is indicated by the downward sloping isentropes east of Greensboro. A strong jet streak is found over Wilmington and the Cape Hatteras starting at 400 mb. A 40 ms^{-1} isotach in this region supports the 300 mb jet analyzed by NORAPS.

B. 0600 UTC 25 FEBRUARY 1986

The Citation dropsonde observations from the remainder of the previously mentioned mission and the Cape Hatteras rawinsonde locations relative to the positions of the surface low centers at 0600 UTC 25 February are shown in Fig. 28. The eastern low pressure center has rapidly moved to the northeast. Despite the fact that all of the observations are in the vicinity of the western low, the soundings do indicate that the eastern cyclone is beginning to strengthen.

Vertical profiles for D045 and D041 are plotted in Fig 29. The data from D045, located between the two low pressure centers, reveal upper-level subsidence and an associated inversion at 700 mb. An SSI value of 0 indicates that the inversion and subsidence is still rather weak. However, this subsidence may be partially explained by the satellite imagery (Fig. 6) which indicates that the observations at D045 were made close to the developing dry slot associated with the eastern low pressure center.

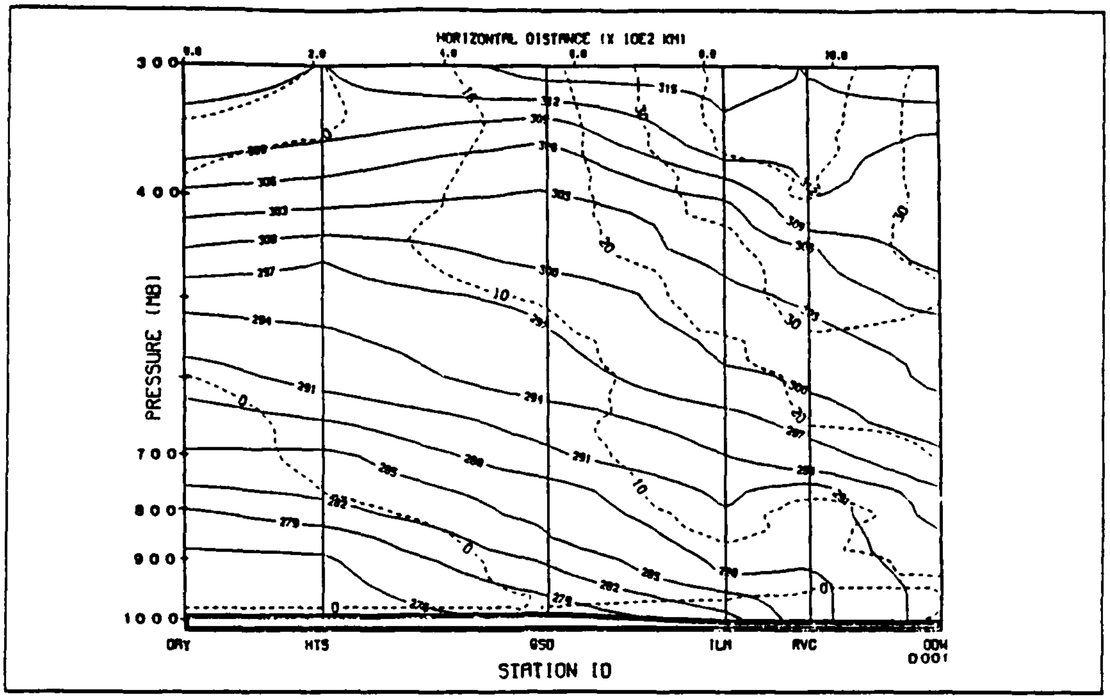

Fig. 27. **Vertical cross-section valid at 0000 UTC 25 February 1986:** Solid lines are isentropes (K) and dashed lines are isotachs (ms^{-1})

Another indication of the strengthening eastern low pressure is the directional shear pattern in the wind observations at D045. Northwest winds are reported at the lowest levels, but shift to westerly winds with height. This backing of the winds is evidence of cold air advection at the lower levels, which in turn indicates that the eastern low is becoming the dominant system.

The sounding from D041, located southwest of the western low pressure center, is similar to the sounding from the northeast in that a weak inversion and subsidence is evident at the upper levels. The SSI value of +2 indicates a slightly more stable environment, however, the satellite imagery (Fig. 6) shows evidence of convection in the region of D041.

Winds at D041 are westerly at all levels, again indicating neutral temperature advection west of the low. The strong upper-level winds, with observed winds at 400 mb of 90 kt, support the intensification of the jet streak suggested by the NORAPS analysis.

The cross-section valid at 0600 UTC 25 February (Fig. 30) follows a similar northwest to southeast line as the previous cross-section through Greensboro, Wilmington,

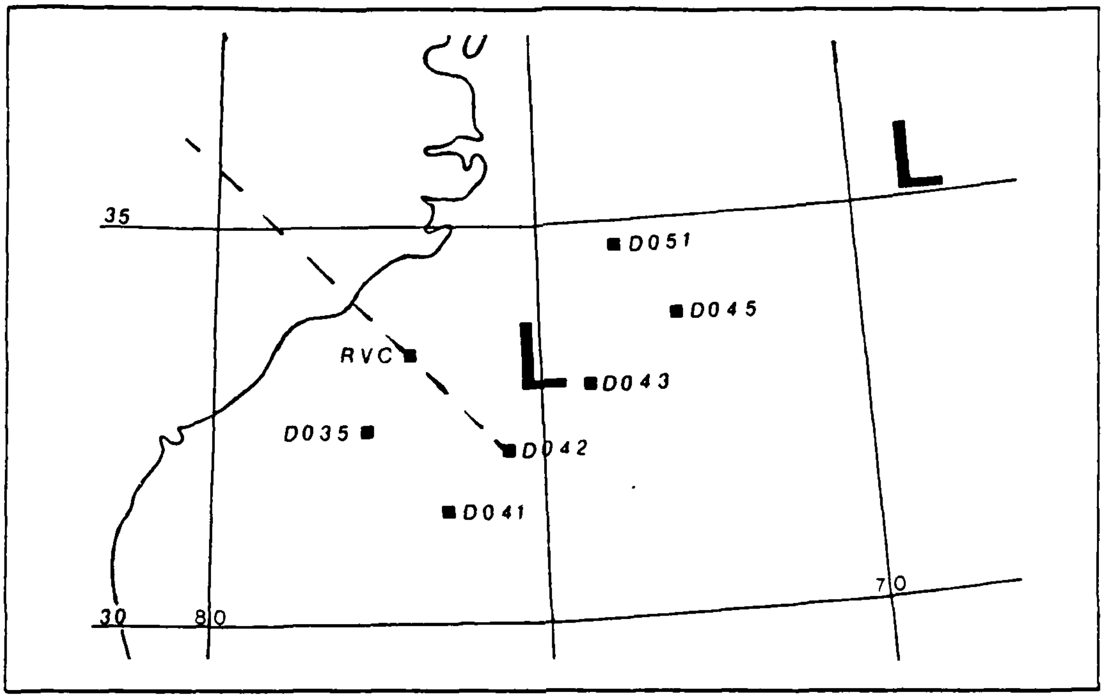

Fig. 28. Citation Dropsonde locations for 0600 UTC 25 February 1986: Citation dropsonde and Cape Hatteras rawinsonde locations relative to the sea-level low pressure center positions

Cape Hatteras and D042 (see dashed line in Fig. 28). The unstable boundary layer remains evident by the vertical isentropes reaching up to 850 mb. Again, it is important to note that this area of instability is well removed from the rapidly developing cyclone and is a result of the destabilizing effect of the warm Gulf Stream waters or possibly a trough extending from the eastern cyclone. The upper-level baroclinic zone has moved eastward, out of the region included in the cross-section, but is still evident in the downward sloping isentropes east of Wilmington.

C. 1200 UTC 25 FEBRUARY 1986

Two GALE missions acquired dropsonde data for 1200 UTC 25 February. The location of these observations relative to the surface low positions are shown in Fig. 31. The NOAA Citation mission flew from 0820 to 1730 UTC, making most of the observations in the vicinity of the western low pressure center. The Air Weather Service (AWS) flew a mission from 0855 to 1606 UTC, making measurements along a path stretching from south of the western low, moving between the two low centers and then

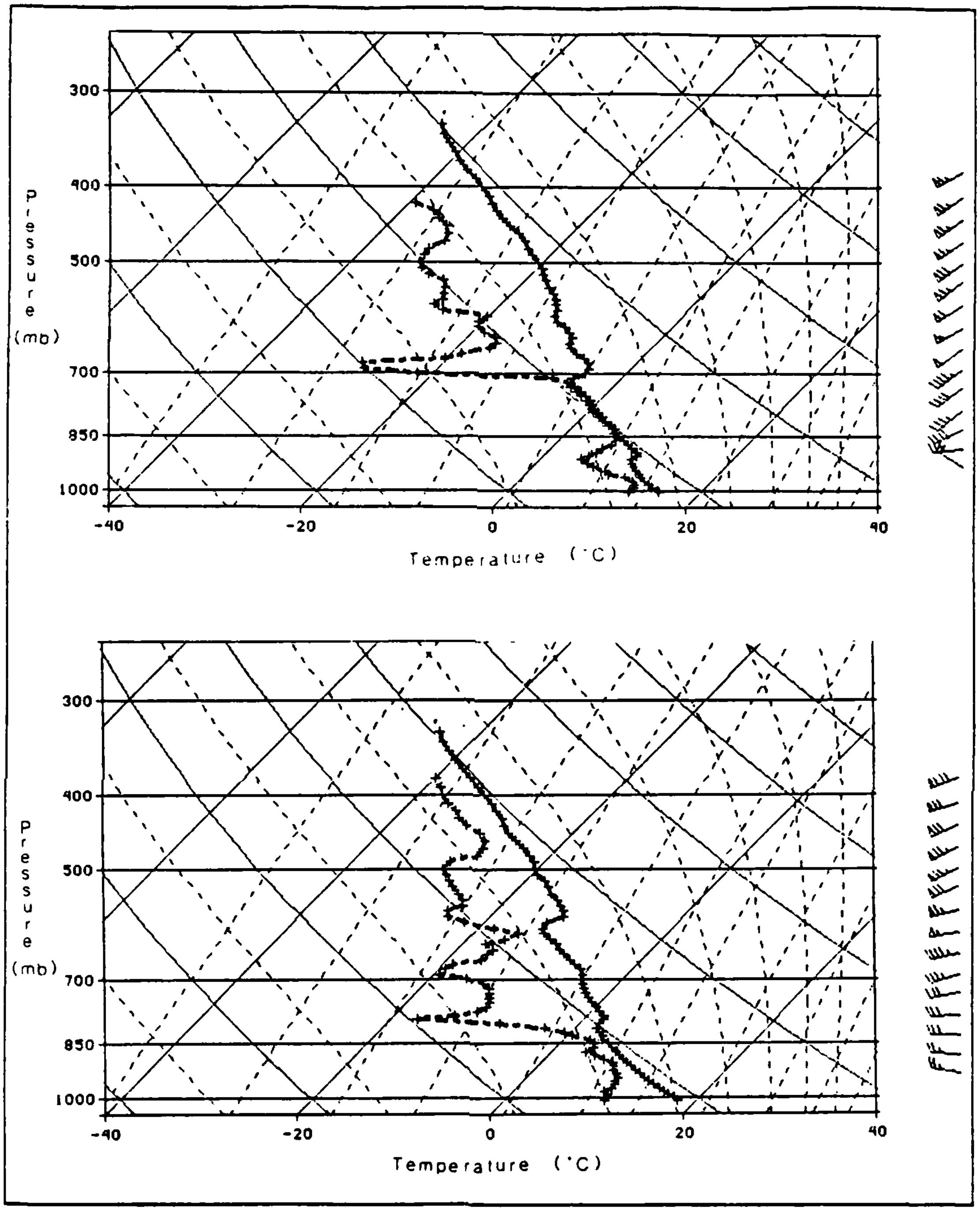

Fig. 29. Citation Dropsonde soundings for 0600 UTC 25 February 1986: D045 (top) and D041 (bottom). See Fig. 28 for dropsonde locations

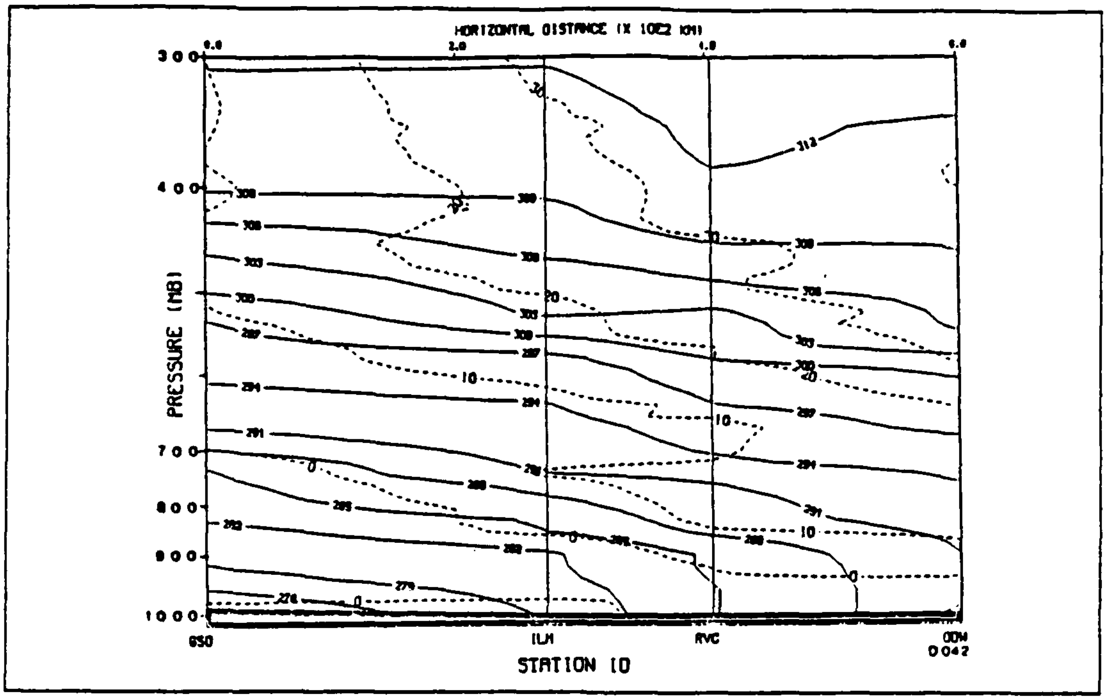

Fig. 30. Vertical cross-section valid at 0600 UTC 25 February 1986: Solid lines are isentropes (K) and dashed lines are isotachs (ms^{-1})

north of the eastern low pressure. The AWS observations were the first made near the eastern cyclone since 0000 UTC 25 February.

The temperature and wind profiles for D113 and D103 are plotted in Fig. 32. The data for D113 indicate a very moist layer from 950 mb to nearly 500 and is a typical sounding of deep convection under the 500 mb trough. In this instance, mid-level forcing is combined with an unstable boundary layer to create the large region of convective activity north and east of the dissipating low seen on the satellite imagery (Fig. 8). Northerly winds at the lower levels back to westerly and southwesterly winds with height indicating cold air advection. Wind speeds are relatively light at the upper levels. An observation of 65 kt at 400 mb suggests that the jet has moved ahead of the long wave trough.

The sounding from D103, located southwest of the western low center, is similar to D113. The winds again back with height leading to cold air advection at the lower levels. Due to its location south of the low, D103 reported a maximum wind of 95 kts at 400 mb. This supports the upper level jet streak exiting the base of the trough as analyzed by NORAPS. Neither D103 or D113 showed any indication of subsidence associated

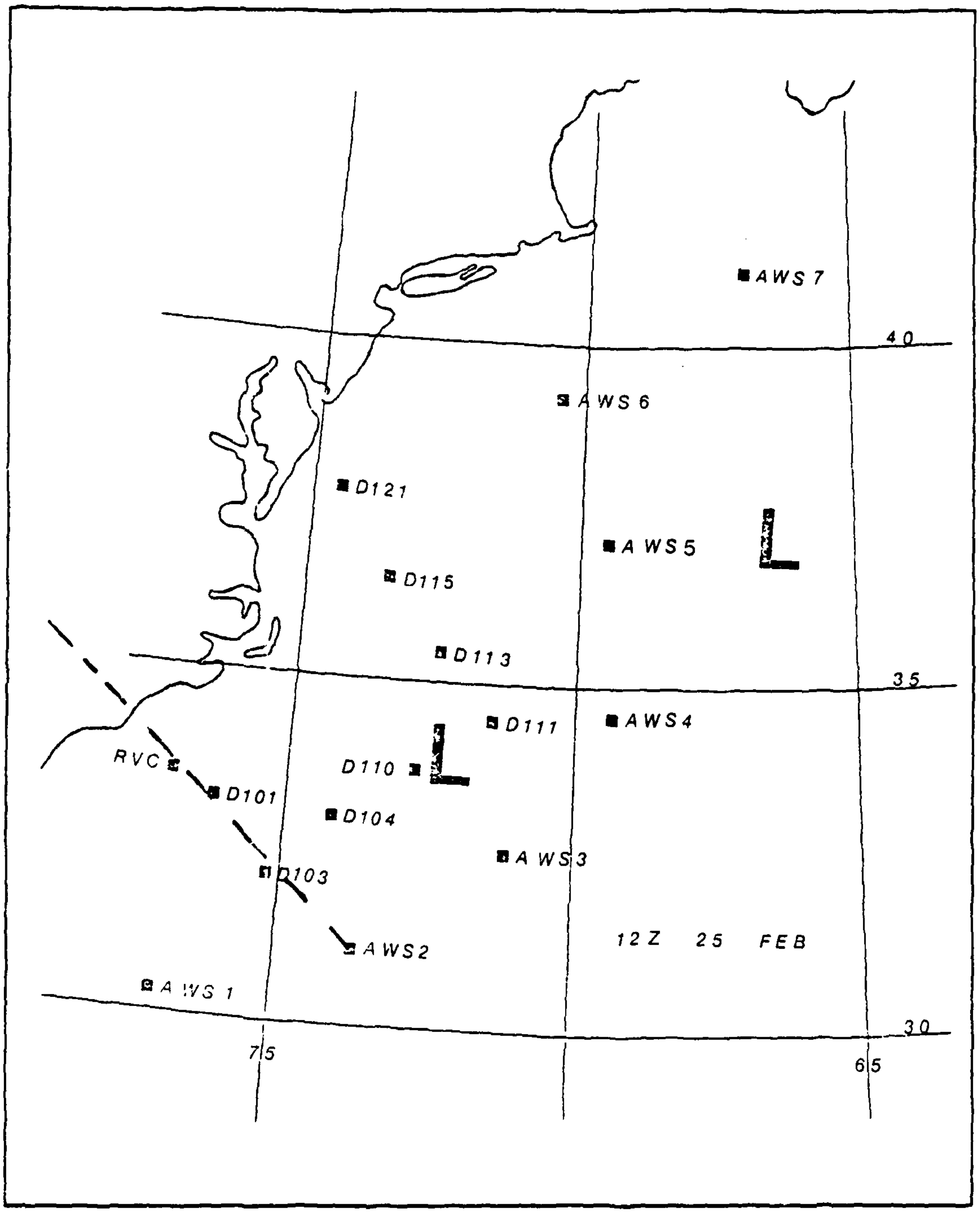

Fig. 31. **Dropsonde locations for 1200 UTC 25 February 1986:** Citation and AWS dropsonde locations relative to the sea-level low pressure center positions

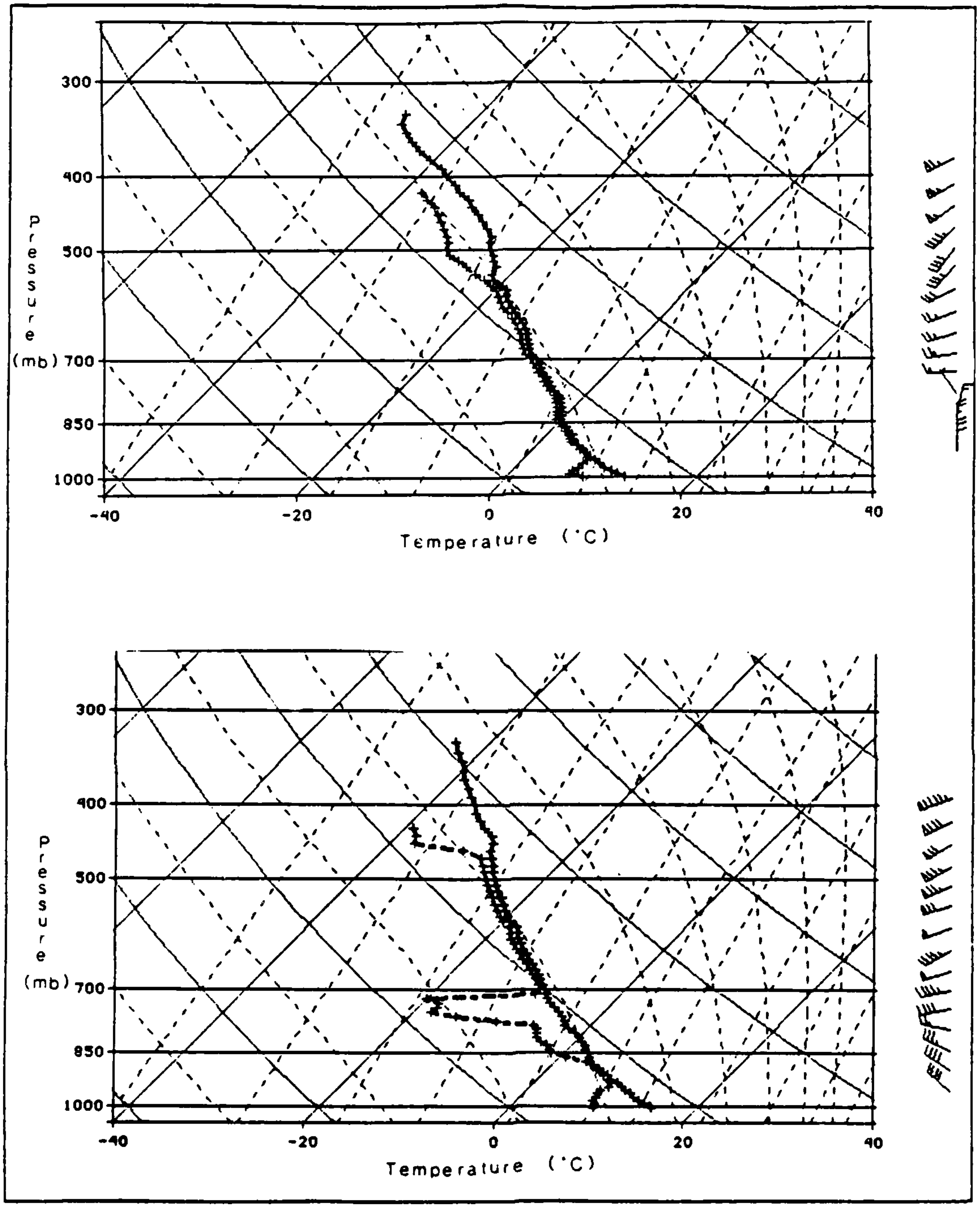

Fig. 32. **Citation dropsonde soundings for 1200 UTC 25 February 1986: D113 (top) and D103 (bottom). See Fig. 31 for dropsonde locations**

with the dry slot. However, this was not the case with several of the AWS dropsondes which were launched further to the east. The soundings from AWS 3, AWS 4, AWS 5 and AWS 6 are shown in Figs. 33-34. No wind data are available for these locations as the dropsondes measured thermal data only. Even without the winds, the structure of these soundings provide key information about the environment between the two lows. In particular, the location of the dry slot associated with the rapidly deepening cyclone is defined.

AWS 3 is located in the cloudy region close to the back edge of the dry slot associated with explosively developing cyclone. The satellite imagery (Fig. 8) indicates a region of upper-level cloudiness as a result of cirrus blowoff from a convective region to the west of AWS 3. Dewpoint depressions less than 1°C reported above 600 mb confirm this observation. However, a weak inversion exists near 950 mb, with a warm, dry level between 950 mb and 600 mb associated with the subsiding air in the dry slot. Because the satellite imagery is rather chaotic during the entire IOP, this observation helps confirm the existence and position of the dry slot.

The satellite imagery indicates that AWS 4 is located in a rather moist environment east of the western low center and southwest of the rapidly developing cyclone. This is reflected in the sounding as a very moist layer above 815 mb. However, levels below 815 mb reveal a weak inversion and low level subsidence.

Comparing the location of AWS 5 to satellite imagery, AWS 5 appears to be in the head of the comma cloud to the west of the explosively deepening cyclone. The comma cloud head is usually characterized by thick, multilayer cloudiness. That is precisely what is indicated by the sounding at AWS 5, namely an extremely moist, convective type sounding.

Finally, the dropsonde from AWS 6, located northwest of the cyclone indicates an extremely moist atmosphere from the surface to 400 mb. The satellite imagery depicts widespread, multilayer cloudiness across this region. The SSI value of +08 indicates a fairly stable environment at this time. However, the vertical temperature and moisture structure of AWS 6 shows the path of saturated ascent a parcel would follow after initially becoming unstable. This profile is typical of the environment north and west of the cyclone.

At 1200 UTC 25 February the vertical cross-section (Fig. 35) is moved slightly to the south (see dashed line on Fig. 31), running through Greensboro, Wilmington, Cape Hatteras, D101, D103, and AWS 2. The boundary layer instability is confined to the

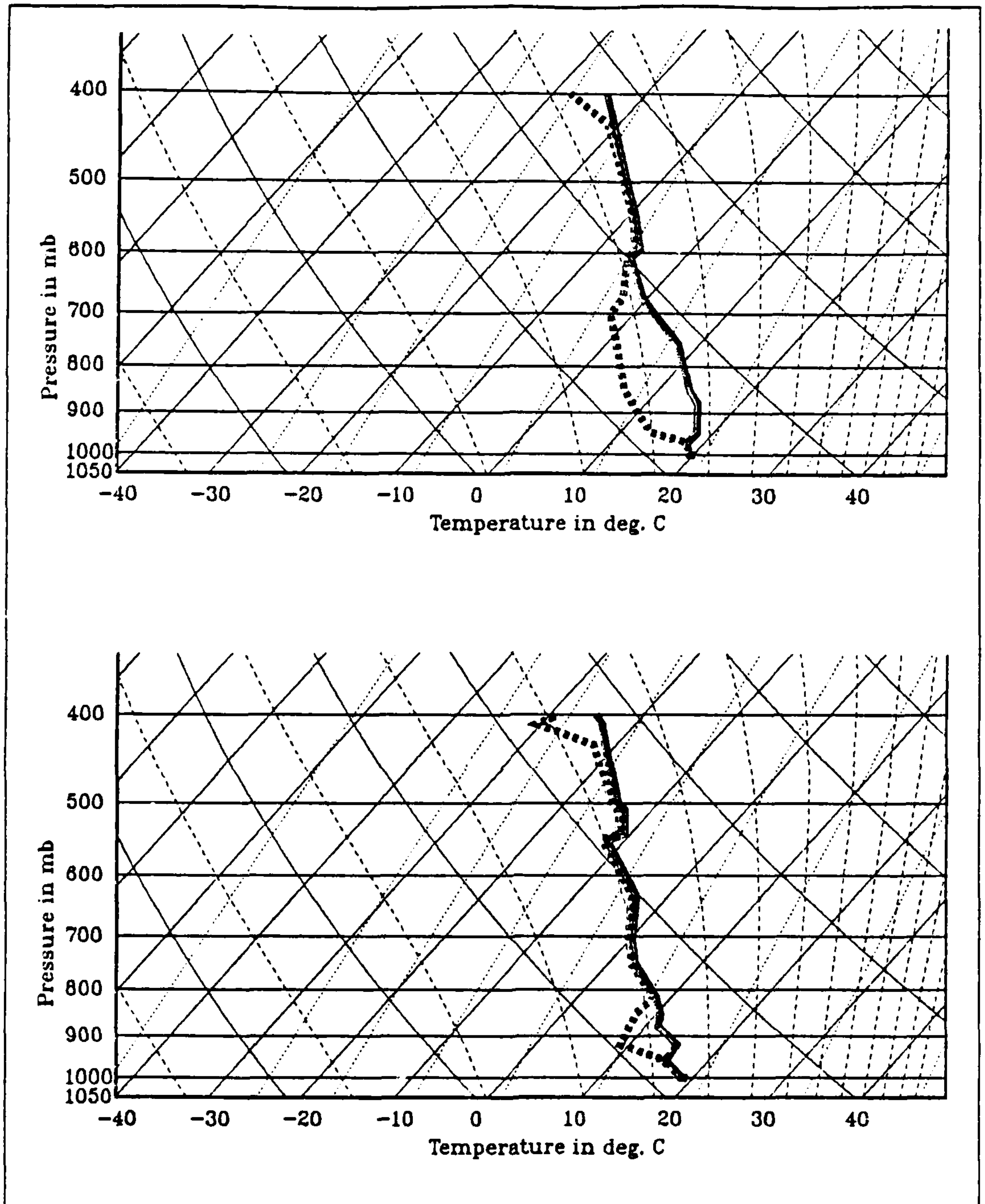

Fig. 33. **Air Weather Service dropsonde soundings for 1200 UTC 25 February 1986:** AWS 3 (top) and AWS 4 (bottom). See Fig. 31 for dropsonde locations.

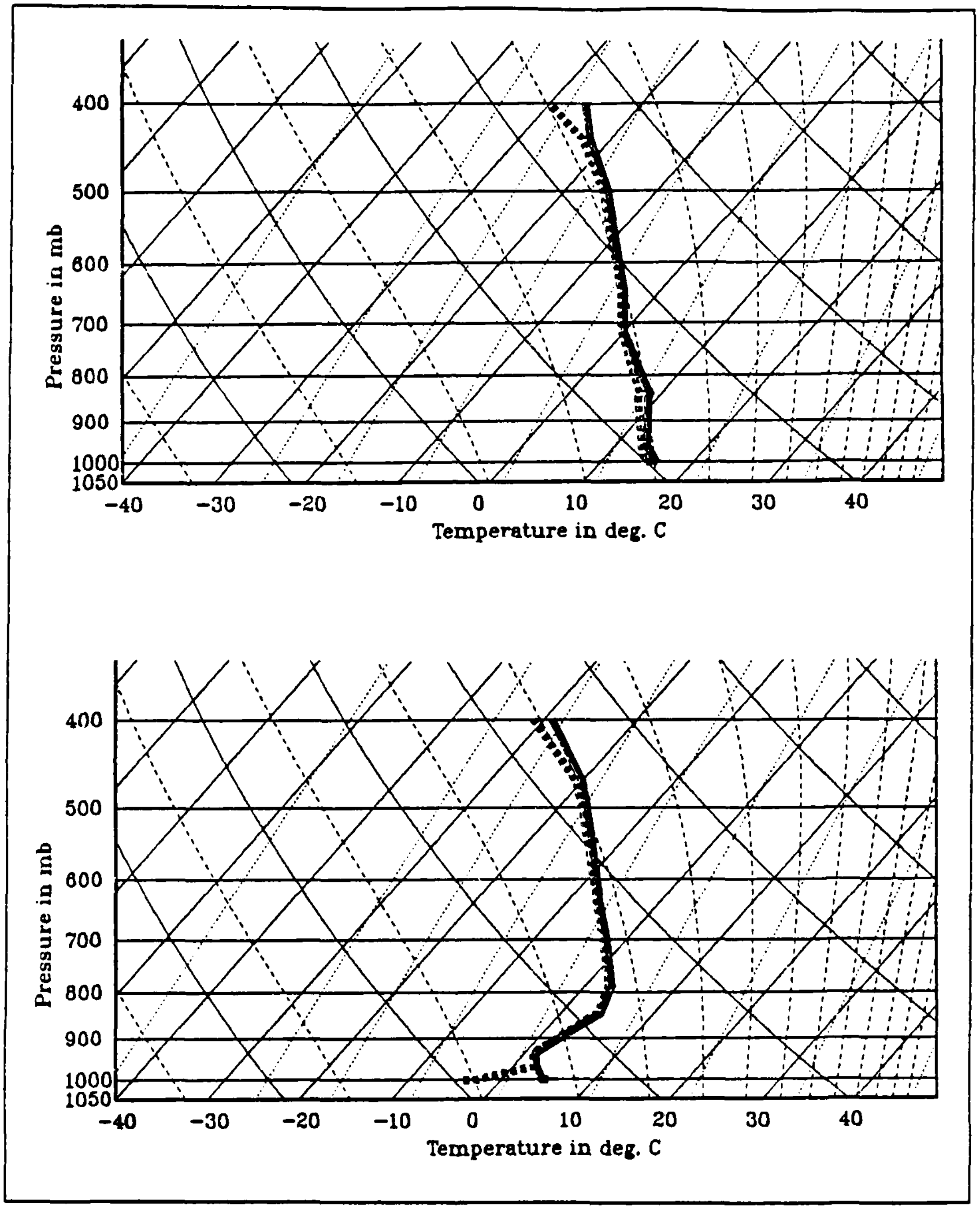

Fig. 34. **Air Weather Service dropsonde soundings for 1200 UTC 25 February 1986:** AWS 5 (top) and AWS 6 (bottom). See Fig. 31 for dropsonde locations.

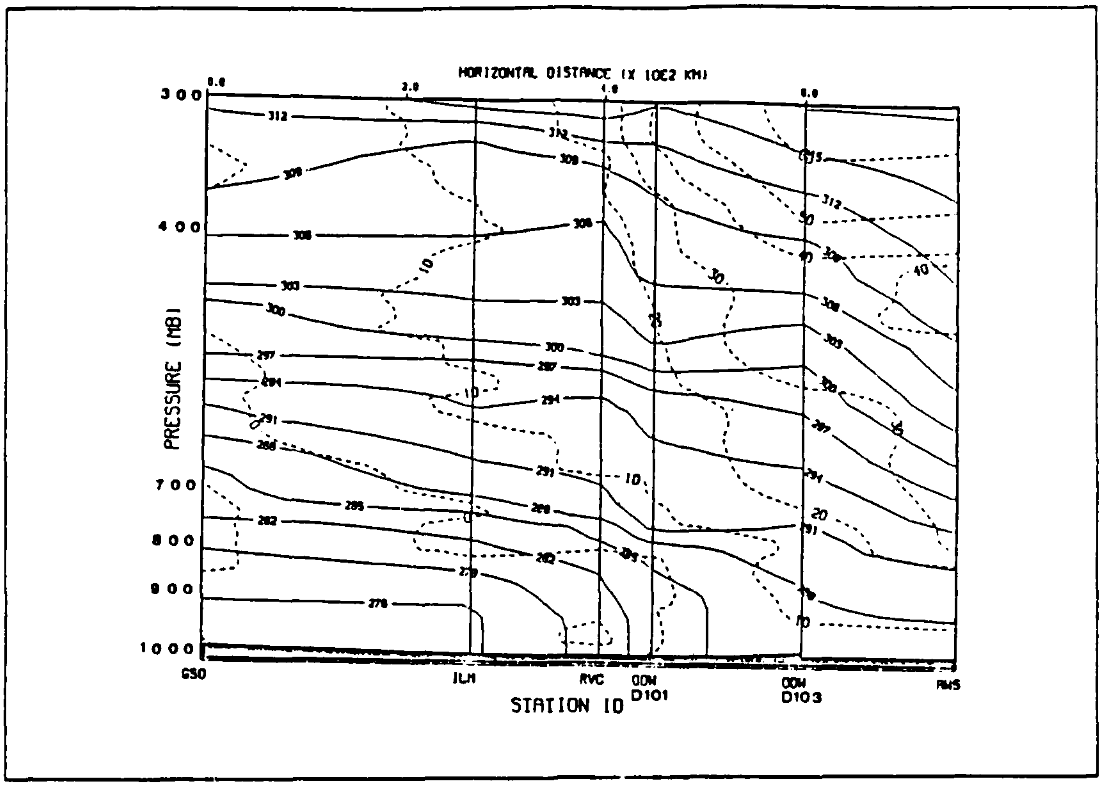

Fig. 35. **Vertical cross-section valid at 1200 UTC 25 February 1986:** Solid lines are isentropes (K) and dashed lines are isotachs (ms^{-1})

region over the Gulf Stream. The upper-level baroclinic zone has continued to move to the east, and is now associated with the sloping isentropes between D001 and AWS 2. The upper-level jet has continued to intensify and is supported by a 60 ms^{-1} isotach over D103 near 300 mb.

D. SUMMARY OF ENVIRONMENTAL DISCUSSIONS

The additional upper-level data acquired during the GALE project, and the soundings and vertical cross-sections produced with these data helped describe the environment over the western North Atlantic Ocean during the first 12 hours of GALE. Several environmental features identified in this region may have contributed to the observed explosive cyclogenesis.

Relatively low Showalter Stability Index values and the low-level structures of the dropsonde temperature profiles indicated that the boundary layer over the Western North Atlantic Ocean, particularly in the vicinity of the western low pressure center, was

characterized by weak instability. This instability shows the effect that the warm water of the Gulf Stream has on the environment and suggests the possibility of an elongated trough over the region as discussed earlier. This fact was also suggested by the vertical orientation of the isentropes depicted in the cross-section analyses. The vertical cross-sections were also helpful in locating and tracking the eastward movement of the upper-level baroclinic zone associated with the surface cyclone. The intensification of the upper-level jet streak, as depicted in the NORAPS analyses, was also supported by the sounding and cross-section data.

Characteristics of individual soundings and comparisons of neighboring soundings were used to infer and define larger structures in the environment. Using this technique, the strength of the two cyclones was inferred and the existence and location to the dry slot associated with the rapidly deepening cyclone was shown.

V. CONCLUSIONS AND RECOMMENDATIONS

A synoptic study of IOP 9 during the GALE project documents that a rapidly deepening cyclone formed off the coast of North and South Carolina. The observed deepening rate of 1 mbh^{-1} for the 24-hour period from 0000 UTC 25 to 0000 UTC 26 February 1986 associated with this storm meets the definition outlined by Sanders and Gyakum (1980) for explosive cyclogenesis.

Using a data base including operationally available data, late arriving ship reports and GALE observations, a set of surface analyses were prepared showing the development and storm track of this system. These analyses revealed a rather complex surface pattern, beginning with a weak low pressure center moving offshore, a secondary circulation developing ahead of this center, and an old frontal boundary to the east of both of these systems. As time progressed, the secondary low became the dominant weather system, eventually experiencing explosive deepening. One of the most significant features evident from the analyses is the southerly flow of warm moist air ahead of the surface cold front.

Dropsonde and rawinsonde observations acquired by GALE participants were used to supplement the upper-level data base over the ocean. These data was then analyzed using NORAPS and the optimal interpolation of objective analysis. The results of these analyses showed the development of a strong upper-level jet streak and a large area of positive vorticity advection associated with the developing system. Significant low-level warm advection in the vicinity of the deepening low was also analyzed.

Although the additional GALE observations helped to fill the data void over ther western North Atlantic Ocean, most of the observations were concentrated around the low center that moved offshore and eventually dissipated. Very little data were acquired in the vicinity of the explosively developing cyclone. As a result, uppper-level features like the jet streak and vorticity advection were underestimated in the region.

The dropsonde data proved to be invaluable in determining the existence of the two sea-level lows and provided useful information about the environment in which the cyclones developed. Vertical soundings and cross-sections showed an initially unstable environment near the western low pressure center, the intensification of the upper-level jet and the upper level baroclinic zone moving through the region. Soundings were also used to locate the dry slot associated with the rapidly deepening storm.

From the analyses and the calculated values of vorticity and stability, it is evident that positive vorticity advection at the upper levels contributed to the explosive deepening. Warm air advection and a relatively unstable environment also played a role in the rapid deepening of this system.

This study was performed using the best objective analyses available, however, they are far from perfect. Better optimal interpolation analyses need to be prepared to resolve the upper-level structures in this case. Once this is accomplished, quantitative studies using the the Petterssen Development Equation, the Omega Equation or the Geopotential Tendency Equation can be accomplished to determine the importance of the various terms to explosive cyclogenesis.

A comparison of dropsonde data and satellite sounding data also should be accomplished. The quality of some of the dropsonde reports, particularly the sea-level pressure observations, are suspect. This was noted in the discussion of the surface development of the cyclone. Satellite sounding data may be able to verify the dropsonde observations and will also serve as an additional date source for improving the objective analysis of this cyclone.

The explosive cyclogenesis that occurred during IOP 9 was not a classical east coast winter storm or a simple case of one low pressure center deepening rapidly. The interactions between the separate low pressure centers and the specific reasons for the explosive deepening are difficult to determine. However, these difficulties only serve to make this case more interesting and challenging to study.

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